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A FORMULA FOR COMPARING ANNUAL DAMAGING ULTRAVIOLET (DUV) RADIA--ETC(U)

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16. Abstract

A simple formula is developed in this paper for the relative annual damaging ultraviolet radiation (DUV) dose at different tropical and mid-latitude sites. The formula consists of six multiplicative factors which include the effects of amount of ozone, latitude, altitude, cloudiness, ground albedo, and amount of aerosols. A seasonal ozone variation factor is introduced to modify the tropical relative DUV formula for application to mid-latitude sites. The approach involves correlations of sometimes sparse data, and remains to be validated in the general sense.

The formula should be useful, where more exact data are not available, in studies of the effects of solar ultraviolet radiation--and its possible increase from a reduction in stratospheric ozone--on land and marine ecological systems and skin cancer incidence in white Caucasian populations.

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ABSTRACT

A simple formula is developed in this paper for the relative annual damaging ultraviolet radiation (DUV) dose at different tropical and mid-latitude sites. The formula consists of six multiplicative factors which include the effects of amount of ozone, latitude, altitude, cloudiness, ground albedo, and amount of aerosols. A seasonal ozone variation factor is introduced to modify the tropical relative DUV formula for application to mid-latitude sites. The approach involves correlations of sometimes sparse data, and remains to be validated in the general sense.

The formula should be useful, where more exact data are not available, in studies of the effects of solar ultraviolet radiation--and its possible increase from a reduction in stratospheric ozone--on land and marine ecological systems and skin cancer incidence in white Caucasian populations.

FOREWORD

This paper was prepared for the High Altitude Pollution Program of the Federal Aviation Administration under Contract No. DOT-FA77WA-3965.

The author is indebted to Dr. Ernest Bauer, Mr. Henry Hidalgo, and Dr. R. C. Oliver of IDA for their critical reviews of this paper. He is especially grateful to Dr. R. C. Oliver who suggested extending the tropical relative DUV formula to mid-latitude (Chapter 3). The document as it stands is the responsibility of the author. Comments and criticisms are invited.

CONTENTS

FIGURES

TABLES

SUMMARY

A formula is developed in this paper which can be used to compare the annual damaging ultraviolet radiation (DUV) doses at different geographical sites. Relative DUV dose plays an important role in studies of the effects of solar ultraviolet radiation--and its possible enhancement by stratospheric ozone depletion--on marine ecosystems, agricultural crops, skin cancer incidence in white Caucasians, etc. Such a formula also can be used to select sites for future solar UV-B measurements. The formula consists of six multiplicative factors which include the effects of amount of ozone, latitude, altitude, cloudiness, ground albedo, and amount of aerosols.

The formula is based on the assumption that D, the relative annual damaging ultraviolet radiation dose (DUV) at a given site can be expressed as the product of six separable multiplicative factors, i.e.,

$$D = D_\tau \; D_L \; D_h \; D_C \; D_A \; D_\beta \; ,$$

where the subscripts τ, L, h, C, A, and β refer, respectively, to the average amount of ozone, latitude, altitude, average cloud amount, ground albedo, and amount of aerosols. The reference value of D is unity, corresponding to an equatorial sea-level site with an average annual amount of ozone of 240 m. atm-cm, no clouds, zero ground albedo, and standard atmosphere. The two most significant factors, D_τ and D_L, are empirically shown in the paper to be independent of each other. The remaining factors are correction factors which could involve some interdependency effects. While the magnitudes of these effects

are probably of second order, the validity of the formula remains to be demonstrated in a general sense.

The expressions derived for the six factors are as follows:

$$D_\tau = 1 - 0.00484\ (\tau - 240)$$

in the tropics and

$$D_\tau = 9.80 \times 10^{-6}\ \tau^2 - 1.0186 \times 10^{-2}\ \tau^2 + 2.886$$

at mid-latitudes where τ is the annual average ozone thickness in m. atm-cm.

$$D_L = e^{-3.74 \times 10^{-4}\ L^2}$$

in the tropics and

$$D_L = e^{-3.74 \times 10^{-4}\ L^2\ \alpha\ (\tau,\ L)}$$

at mid-latitudes where L is the latitude in degrees and $\alpha\ (\tau, L)$ is a correction factor (Eq. 30).

$$D_h = 1 + 0.060\ h$$

where h is the altitude in degrees.

$$D_C = 1 - 0.50\ C$$

where C is the average cloud amount

$$D_A = 1 + 0.50\ A$$

where A is the ground albedo

$$D_\beta = 1 - 0.093\ (\beta - 1)$$

where β is the ratio of the amount of aerosols to the standard amount of aerosols.

For mid-latitudes, it was found necessary to introduce an additional seasonal ozone correction factor,

$$1 + \rho\ (\tau,\ L)\ ,$$

where $\rho\ (\tau,\ L)$ is given by Eq. (37) on p. 43 for the Southern Hemisphere and by Eq. (43) on p. 46 for the Northern Hemisphere.

The ozone data base used in this paper was the *Atlas of the Global Distribution of Total Ozone July 1957-June 1967* (Ref. 1). Calculations of DUV doses by A.E.S. Green and T. Mo in the CIAP program (Refs. 2 and 11) provided basic input information essential to many of the empirical relationships derived.

A comparison of the relative annual DUV dose was made for 19 selected tropical sites, considering only the effects of amount of ozone, latitude, and altitude. It was found that Cerro de Pasco, Peru, a mining town at an altitude of 4.40 km and a latitude of 10°S, and Quito, Ecuador, on the equator at an altitude of 2.85 km, both have a relative annual DUV approximately 80 percent higher than Key West, Florida, which is a sea-level site at a latitude of 24½°N.

I. INTRODUCTION

The objective of this paper is the derivation of a formula which can be used to compare annual damaging ultraviolet radiation (DUV) dose at different geographical sites. In Chapter II, a formula for tropical sites is derived, and a modification of this formula for mid-latitude sites is derived in Chapter III. The principal factors considered are amount of ozone (τ), latitude (L), altitude (h), cloudiness (C), ground albedo (A), and amount of aerosols (β). In this exploratory effort, it was found that for tropical sites, these six factors, while not all independent of one another, can to a first approximation be combined in a product formula, i.e.,

$$D = D_\tau \; D_L \; D_h \; D_C \; D_A \; D_\beta \; , \tag{1}$$

where D is the relative annual damaging ultraviolet radiation dose and each of the component factors are referenced to an appropriate baseline value of unity. All relative DUV doses used in this paper represent the solar energy incident on a horizontal surface, weighted by the erythemal response spectrum.

A formula for mid-latitude sites was derived by modifying two of the above six multiplicative factors and introducing an additional seasonal ozone variation factor (Chapter III).

Tropical sites are of special interest in considering the potentially harmful effects of a reduction in stratospheric ozone induced by fluorocarbons, future stratospheric aircraft fleets, etc. Near the equator the protective ozone thickness has a relatively stable minimum value and the sun a high

noontime elevation angle throughout the year. Consequently, a large portion of the earth's surface receives a maximal annual dose of biologically damaging ultraviolet (DUV) radiation (42 percent of the earth's surface lies between latitudes 25°N and 25°S). In the event of a significant reduction in global stratospheric ozone, the equatorial zone could be confronted with levels of ultraviolet radiation perhaps not experienced on earth for billions of years. While it is possible to equate the future new level of ultraviolet radiation at a sea-level mid-latitude region to that currently received at a sea-level latitude closer to the equator, this latitude translation cannot be made at the equator. Migration for stressed equatorial ecological systems at sea level is therefore not a possibility.* It would be highly desirable to investigate the behavior of ecological systems in those equatorial regions of maximal ultraviolet radiation. The initial motivation for this paper was the derivation of a simple formula which can be used to identify those low-latitude sites which today are receiving the highest annual damaging ultraviolet radiation doses on earth.

While tropical sites are of great ecological interest, the vast majority of the white Caucasian populations, which are susceptible to solar-ultraviolet-induced skin cancer, are to be found living at mid-latitude sites. A quick method of calculating annual relative DUV dose may be of some use in comparing skin cancer incidence at various geographic sites. However, it must be recognized that while many ecological systems can be exposed daily to the full DUV dose on the ground, humans receive only a fraction of the dose, depending on individual exposure and clothing habits.

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*Downward altitude migration of ecosystems that have adapted to higher elevations could provide some limited relief. Marine animals might, where depth permits, move to deeper waters.

II. TROPICAL SITES

A. OZONE

The thickness of the ozone column, τ, varies with latitude. In. Fig. 1 (from Ref. 1) is shown the global distribution of total ozone averaged over the 10-year period starting in July 1957. The worldwide distribution of the stations used to obtain data is also indicated in the figure. The contour map indicates that the northern part of South America and the central part of Africa had the minimum average total ozone column of approximately 240 x 10^{-3} cm, or 240 m. atm-cm, for the period 1957-1967. If only the ozone factor is considered, the highest ultraviolet radiation levels could be expected to be found within the 240 m. atm-cm contour of Fig. 1.

The use of an average value of total ozone in the formula derived below for the tropics would be inappropriate for regions outside the tropical zone because of the large ozone fluctuations with season. The effect of season on amount of ozone is minimal near the equator, as indicated in Fig. 2 (from Ref. 1). Also, differences in total average ozone of only approximately 10 m. atm-cm are to be found at the equator, while a difference of 70 m. atm-cm is found between longitudes 130°E and 40°E at a latitude of 50°N (Fig. 1).

The ozone function D_τ at the equator is shown as a function of τ in Fig. 3. The five circled points shown are based on the sum of the 12 monthly DUV tabulated values* calculated by T. Mo and A.E.S. Green (Ref. 2) at sea level for a standard amount of

*Includes both scattered and direct solar radiation incident on a flat horizontal surface.

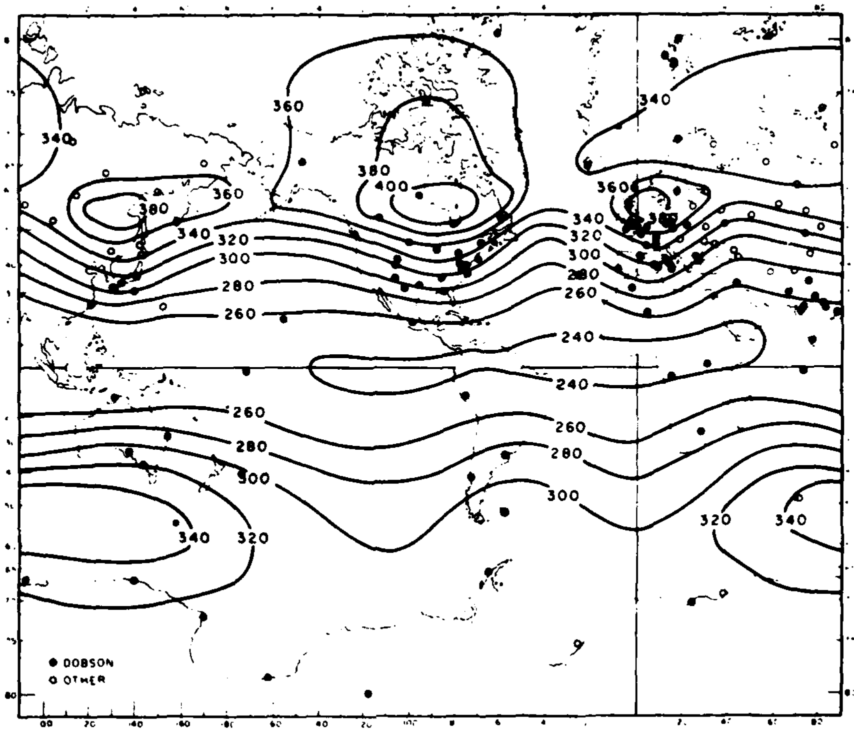

FIGURE 1. Global distribution of total ozone averaged over the period 1957-1967. (Source: Ref. 1)

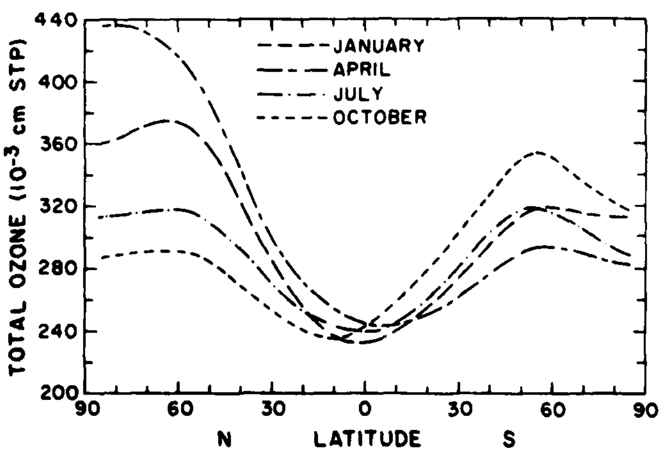

FIGURE 2. Latitudinal variation of average total ozone averaged over the period 1957-1967. (Source: Ref. 1)

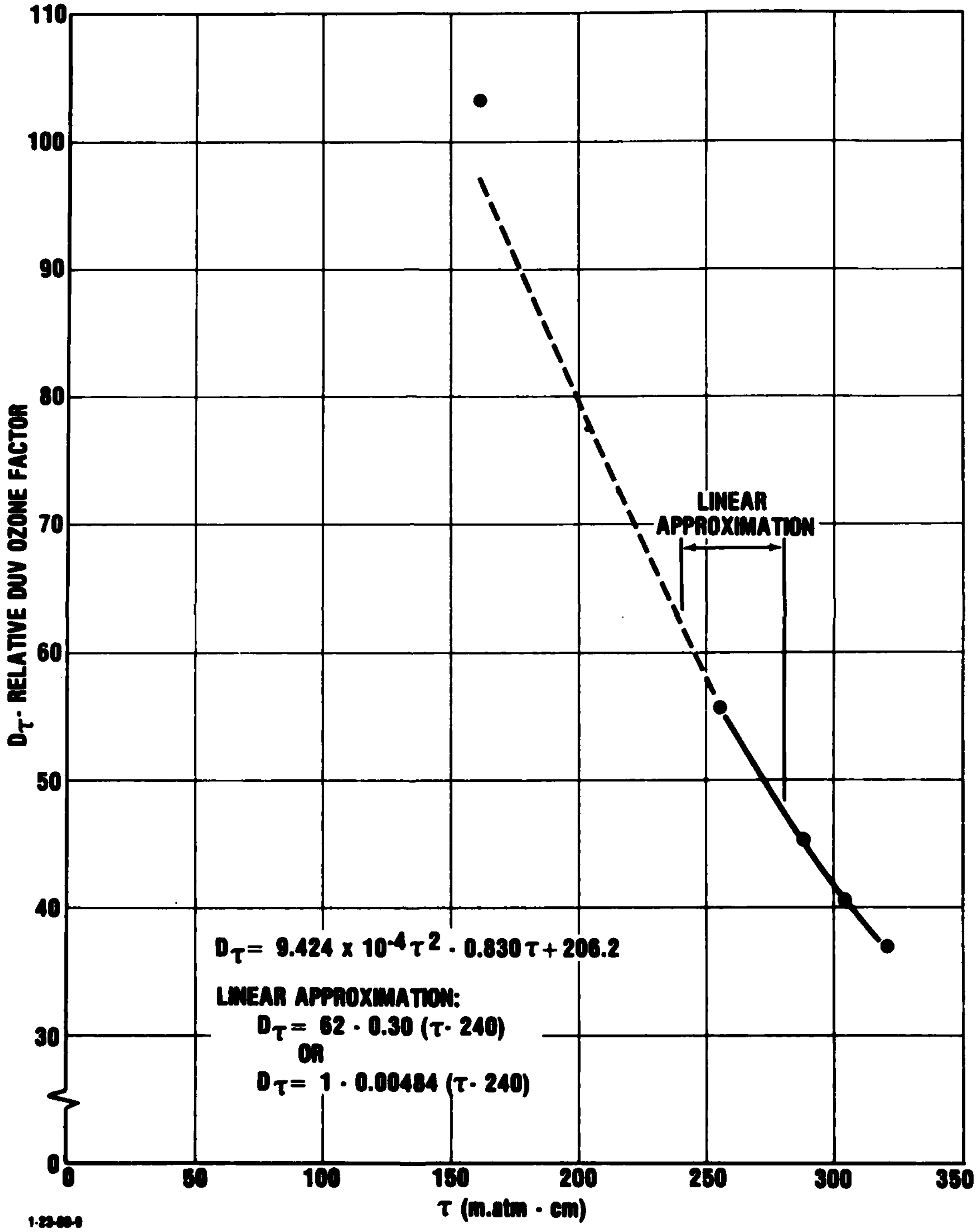

FIGURE 3. Relative DUV vs ozone thickness at the equator

aerosols in a clear atmosphere with zero ground albedo. A parabolic fit to the three calculated points at 256, 288, and 320 m. atm-cm was made, leading to

$$D_\tau = 9.424 \times 10^{-4} \tau^2 - 0.830 \tau + 206.2 \ . \qquad (2)$$

However, a simpler linear approximation can be used here to cover the narrow band of expected values of τ near the equator. The following linear equation is adequate for the purpose of this paper to cover the tropical range of 240 - 280 m. atm-cm (10-year average).

$$D_\tau = 62 - 0.30 (\tau - 240) \ . \qquad (3)$$

Dividing by 62, we have the relative ozone value function

$$D_\tau = 1 - 0.00484 (\tau - 240) \ . \qquad (4)$$

Eq. (4) can be used to compare the annual DUV at two sites of different longitude along the equator (L = 0°) if they differ in their τ value and all of the other four factors are assumed to be equal.

The second term in Eq. (4) gives the fractional decrease in moving from a site having 240 m. atm-cm of ozone to one with a higher value of τ. For every 1 percent increase in ozone along the equator, there is a 1.16* percent decrease in DUV (as compared to approximately 2 percent decrease for mid-latitude sites).

B. LATITUDE

In Fig. 4 the variation of relative DUV with the square of the latitude (L^2) is plotted on semi-log paper for values of τ

*In agreement with Fig. 4.4.81 in *The Report of the Committee on Meteorological Effects of Stratospheric Aircraft (COMESA) 1972-1975*, Part 2, 1975.

between 256 and 320 m. atm-cm. The circled points are again based on the calculations of T.E. Mo and A.E.S. Green (Ref. 2). There are two significant empirical observations to be made in Fig. 4: (1) for a given value of τ the relative DUV values fall almost exactly on a straight line for latitudes less than 25°, and (2) the slopes of the lines are almost exactly equal. With these two fortuitous observations, it is possible to accurately formulate the relative annual DUV, considering only ozone and latitude, as the product $D_\tau D_L$ where

$$D_L = e^{-3.74 \times 10^{-4} L^2} , \qquad (5)$$

and L is in degrees.

With Eqs. (4) and (5) it is possible to compare the relative DUV for any two tropical sites in Fig. 1, assuming the other four factors are equal. Thus, for example, the coastal town of Townsville in Queensland, Australia at a latitude of 19°S with a τ of 260 m. atm-cm (Fig. 1) had, over the period 1957-1967, an average DUV, relative to an equatorial sea-level site in South America or Africa, of

$$(1 - 0.0968)\ e^{-0.135} = 0.78 , \qquad (6)$$

assuming equality of the other three factors, i.e., cloudiness, ground albedo, and amount of aerosols.

C. ALTITUDE

The influence of site altitude on the total (direct + diffuse) ultraviolet flux received at the ground has been investigated by S.V. Venkateswaran et al., (Ref. 3). In Fig. 5 is shown the flux normalized to sea level for wavelengths of 300.4 and 311.4 nm for different solar zenith angles and for altitudes up to 2 km (Ref. 3). As indicated in Fig. 5, flux was found to

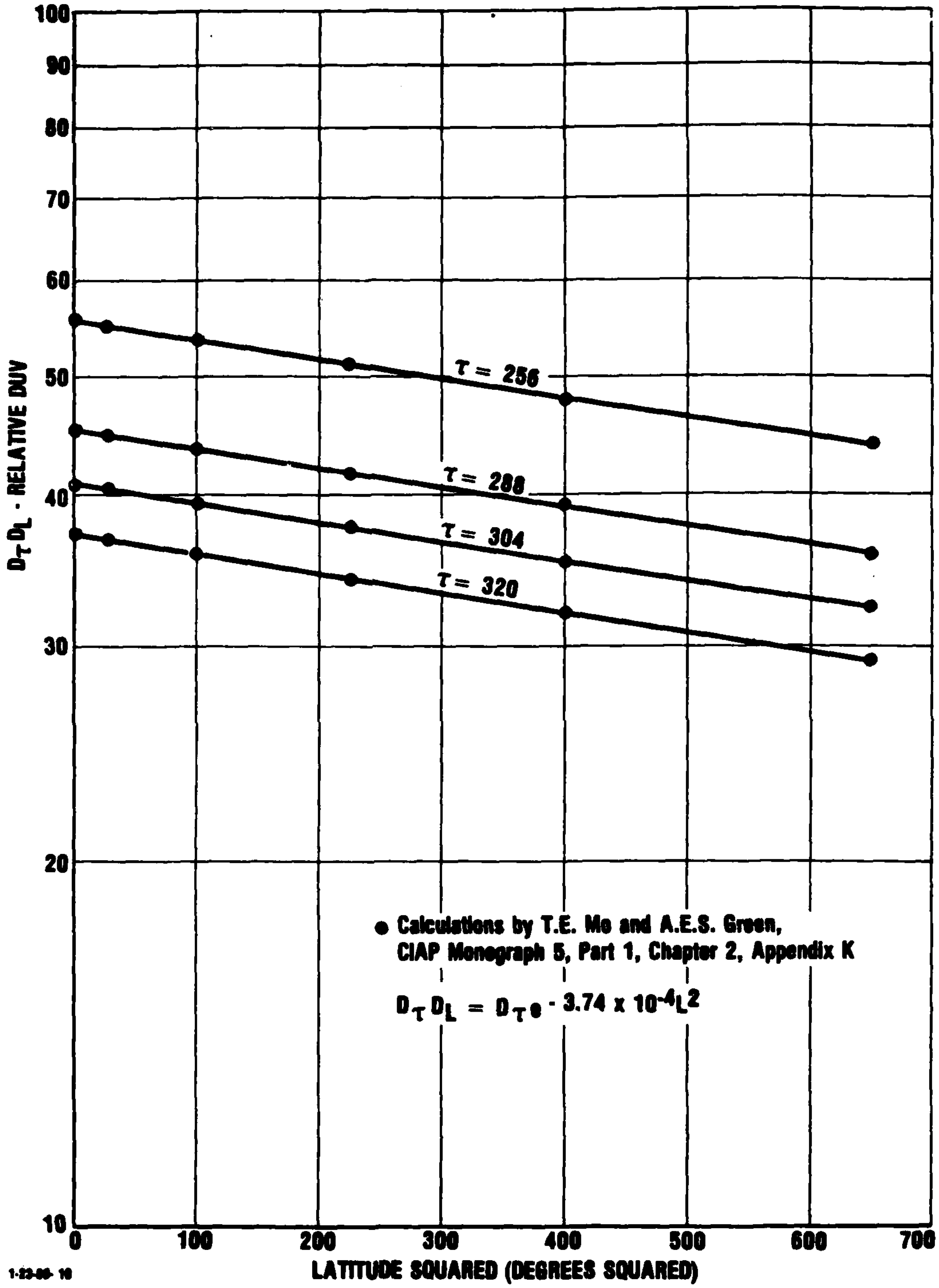

FIGURE 4. Relative DUV vs latitude squared

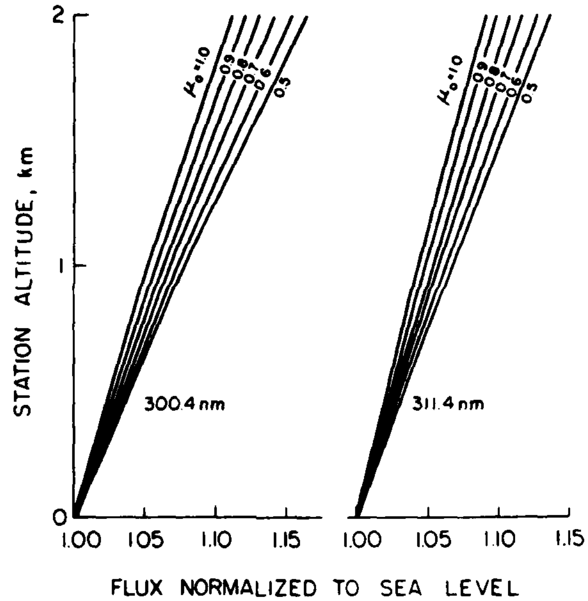

FIGURE 5. The influence of the altitude of the station on the total flux received at the ground is illustrated for two wavelengths (300.4 and 311.4 nm) and for different solar zenith angles θ_0 (= $\cos^{-1} \mu_0$). The fluxes are normalized to sea-level values. The ground albedo is assumed to be zero. (Source: Ref. 3)

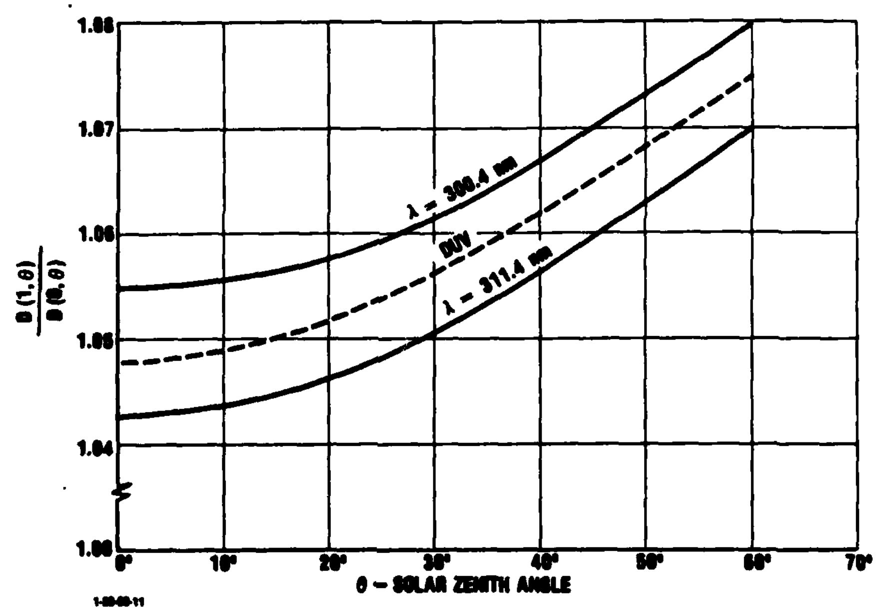

FIGURE 6. Ratio of flux at 1 km altitude to flux at sea level vs solar zenith angle

increase almost linearly with altitude, depending on wavelength and solar zenith angle. While ground albedo was assumed to be zero in these calculations, it was stated that the dependence of the ground albedo effect on site altitude is small for moderate site elevations.

The relative DUV dose D (h, θ) is a function of altitude h and solar zenith angle θ. To obtain a value independent of θ it is necessary to integrate over θ. At the equator the solar zenith angle θ is close to being uniformly distributed* between 0° and 90° because of the constant rotation of the earth. Therefore, the relative altitude DUV function can be approximately calculated from the equation

$$D_h = 1 + h \frac{\int_0^{\pi/2} D(0, \theta) \left[\frac{D(1, \theta)}{D(0, \theta)} - 1\right] d\theta}{\int_0^{\pi/2} D(0, \theta)\, d\theta}, \qquad (7)$$

where D(1, θ) is the relative DUV at an altitude of 1 km and for solar zenith angle θ. The function $\frac{D(1, \theta)}{D(0, \theta)}$ is plotted vs θ in Fig. 6 using the information in Fig. 5 for λ = 300.4 nm and λ = 311.4 nm. Neither of these wavelengths represents the DUV, but a wavelength of approximately 305 nm lying midway between the curves would be representative (Ref. 4).

In Fig. 7 the relative DUV function D(0, θ) is plotted as a function of the solar zenith angle for amounts of ozone between 240 and 400 m. atm-cm (Ref. 5). When plotted on semi-log paper vs $\theta^{2.5}$ (Fig. 8), it is found that D(0, θ) is excellently approximated by

$$D(0, \theta) = e^{-7.2355 \times 10^{-5} \theta^{2.5}} \qquad (8)$$

for $\theta < 60°$ and $240 < \tau < 400$ m. atm-cm.

*Exactly uniformly distributed on two days of the year at the equator.

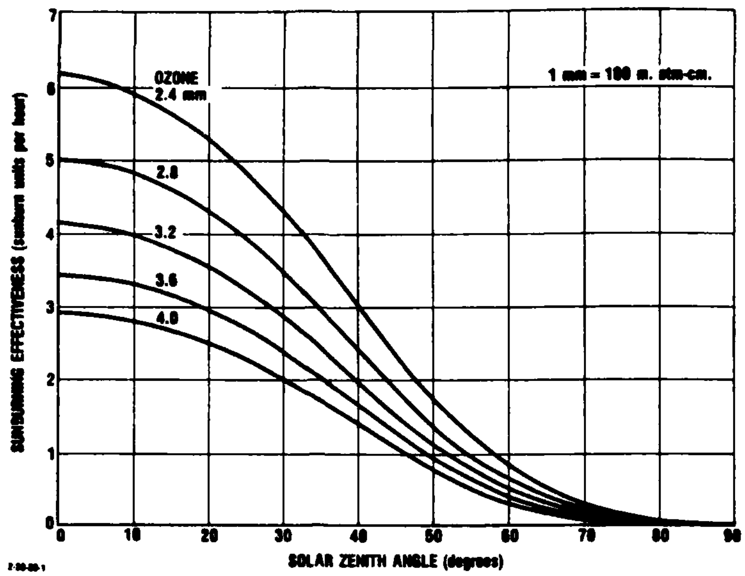

FIGURE 7. Variation of relative erythemal effectiveness on human skin as a function of solar altitude for five ozone values. (Source: Ref. 5)

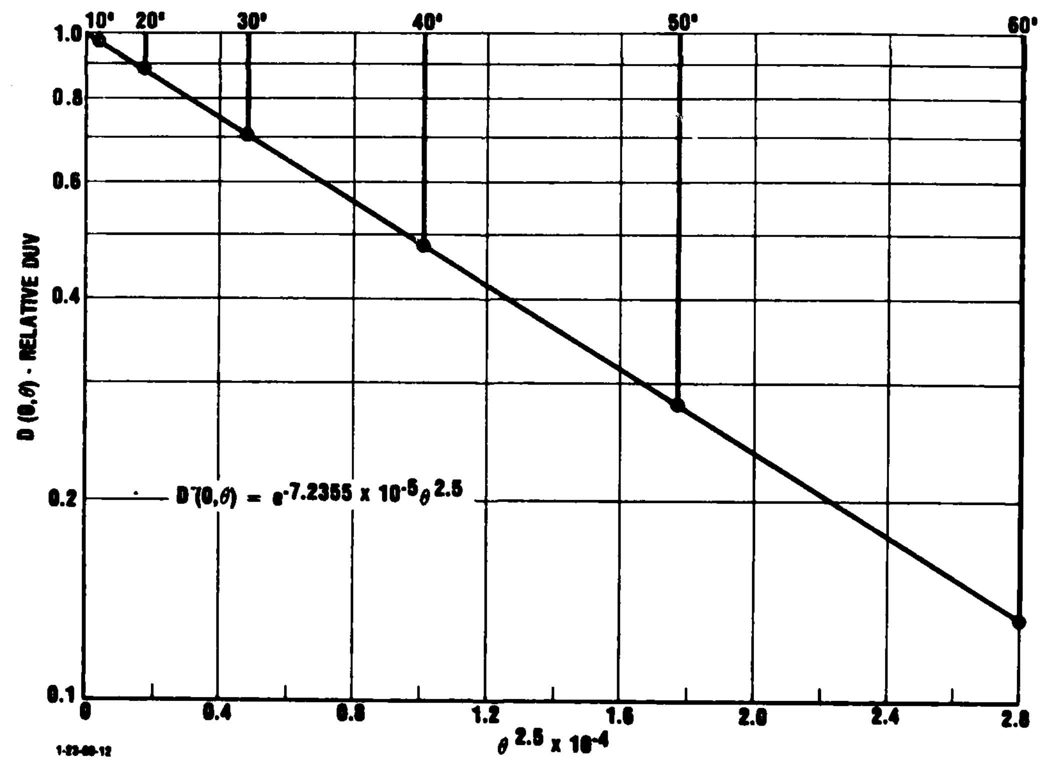

FIGURE 8. Relative DUV vs (solar zenith angle)$^{2.5}$

A check on the validity of Eq. (8) is shown in Fig. 9. The curve of relative DUV vs time of day, as measured by a Robertson Berger meter on a clear day at Mauna Loa, Hawaii on August 11, 1974 (Ref. 6), is seen to match remarkably closely the Eq. (8) values or the empirical curve of Fig. 7. To locate the Eq. (8) values in Fig. 9, the maximum solar zenith angle was estimated to have occurred at 12:12 PM and each 10° of solar zenith angle was assumed to correspond to 43.5 minutes of time.*

The Mauna Loa observatory is located on a mountain top at an elevation of approximately 4 km. Fig. 9 suggests that the dependence of relative DUV on solar zenith angle θ is, to a first approximation, independent of altitude h, i.e.,

$$D(h, \theta) = k\, D(0, \theta) \tag{9}$$

where k is a constant. Numerical integration of Eq. (7), using Fig. 6 and the λ = 300.4 nm curve of Fig. 5, yielded

$$D_h = 1 + 0.0605\, h \quad . \tag{10}$$

Since the λ = 311.4 nm curve is approximately 1 percent below the λ = 300.4 nm curve in Fig. 6, the interpolated D_h function for the DUV curve at the equator is estimated to be

$$D_h = 1 + 0.055\, h \; . \tag{11}$$

In view of the approximation in Eq. (7) that assumed the sun reaches the zenith every day, and that furthermore an equation is desired which is representative of non-equatorial latitudes, Eq. (11) is rounded off in an upward direction to

$$D_h = 1 + 0.060\, h \quad . \tag{12}$$

*The length of day at 20°N latitude is 13.03 hr on August 11.

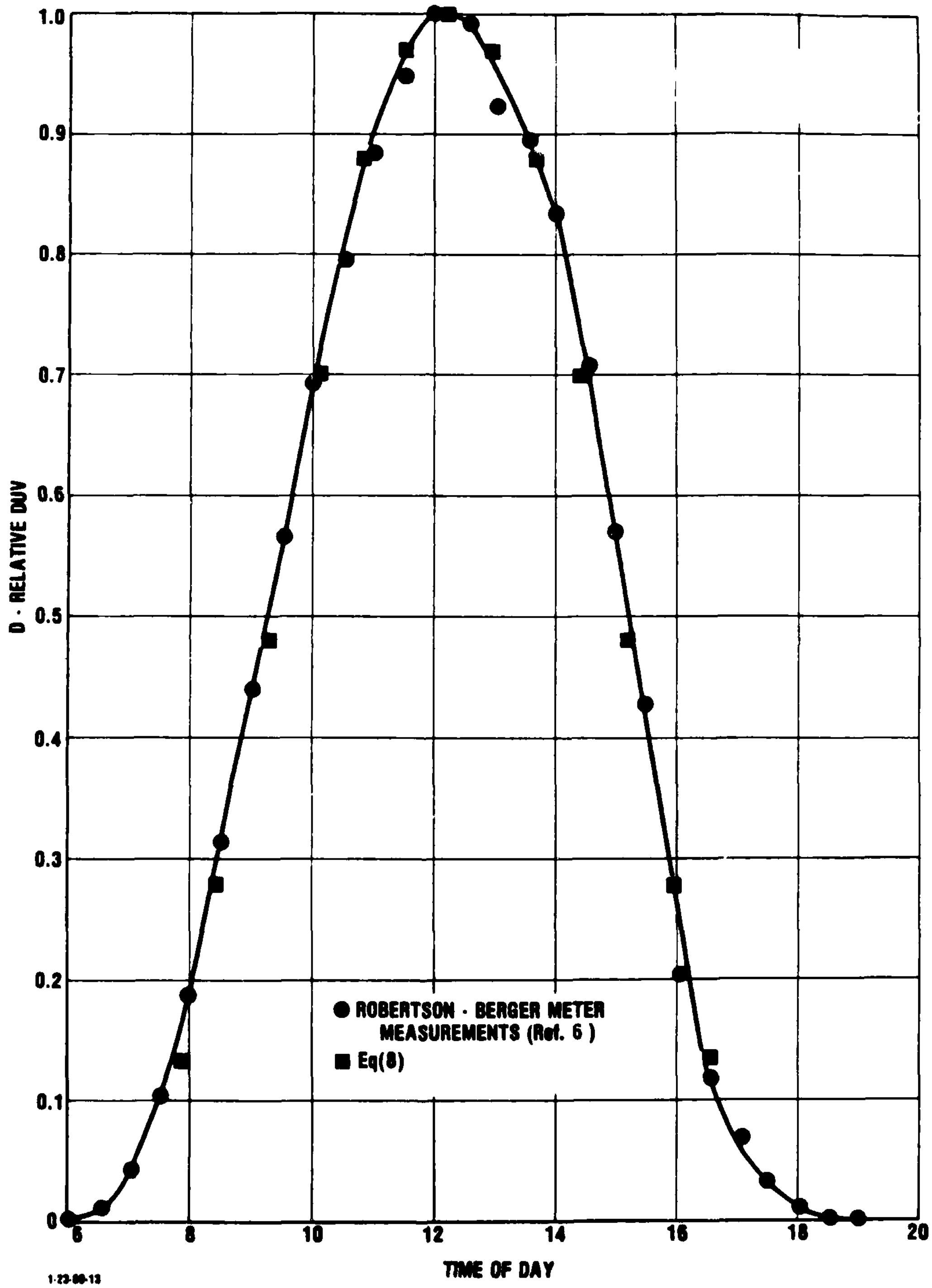

FIGURE 9. Relative DUV vs time of day as measured on August 11, 1974 at Mauna Loa Observatory, Hawaii. (Source: Ref. 6)

An error in the coefficient of h would have a maximum effect on the value of D_h at a maximum value of h. Hence, at h = 4 km, a 5 percent error in the coefficient of h would correspond to only a 1 percent error in the value of D_h. It follows that a good approximation for the relative DUV dose for sites at latitudes below 25° is given by

$$D_\tau \, D_L \, D_h = [1 - 0.00484 \, (\tau - 240)] \, (1 + 0.060 \, h) \, e^{-3.74 \times 10^{-4} L^2} \tag{13}$$

assuming cloudiness, ground albedo, and amount of aerosols are equal.

Equation (13) may be used to find the combination τ, L, and h values that will match the unity value of relative DUV at an equatorial site (L = 0°) at sea level (h = 0) with amount of ozone τ = 240 m. atm-cm. The site altitude h required is illustrated in Fig. 10 as a function of latitude L with τ as parameter. Also sketched in Fig. 10 is the approximate altitude limit for biological ecosystems of approximately 5 km, and the approximate upper and lower limits of ozone amount vs latitude as given by Fig. 1. If L = 15° and τ = 255 m. atm-cm, the altitude required to match the relative DUV of a sea-level equatorial site with τ = 240 m. atm-cm, is approximately 3 km. Altitudes considerably higher than 3 km are readily found in populated regions of Peru and Bolivia.

D. CLOUDINESS

The effect of site cloudiness on relative DUV is very complex but it is possible, as shown below, to use some available data to derive a simple approximate formula for D_C.

In Table 1 is listed the annual DUV count, as measured by the Robertson-Berger meter for 10 U.S. sites for the year 1974 (Ref. 6). The Minneapolis daily DUV count for 1974 is illustrated in Fig. 11 (Ref. 6). The complex effect of clouds is

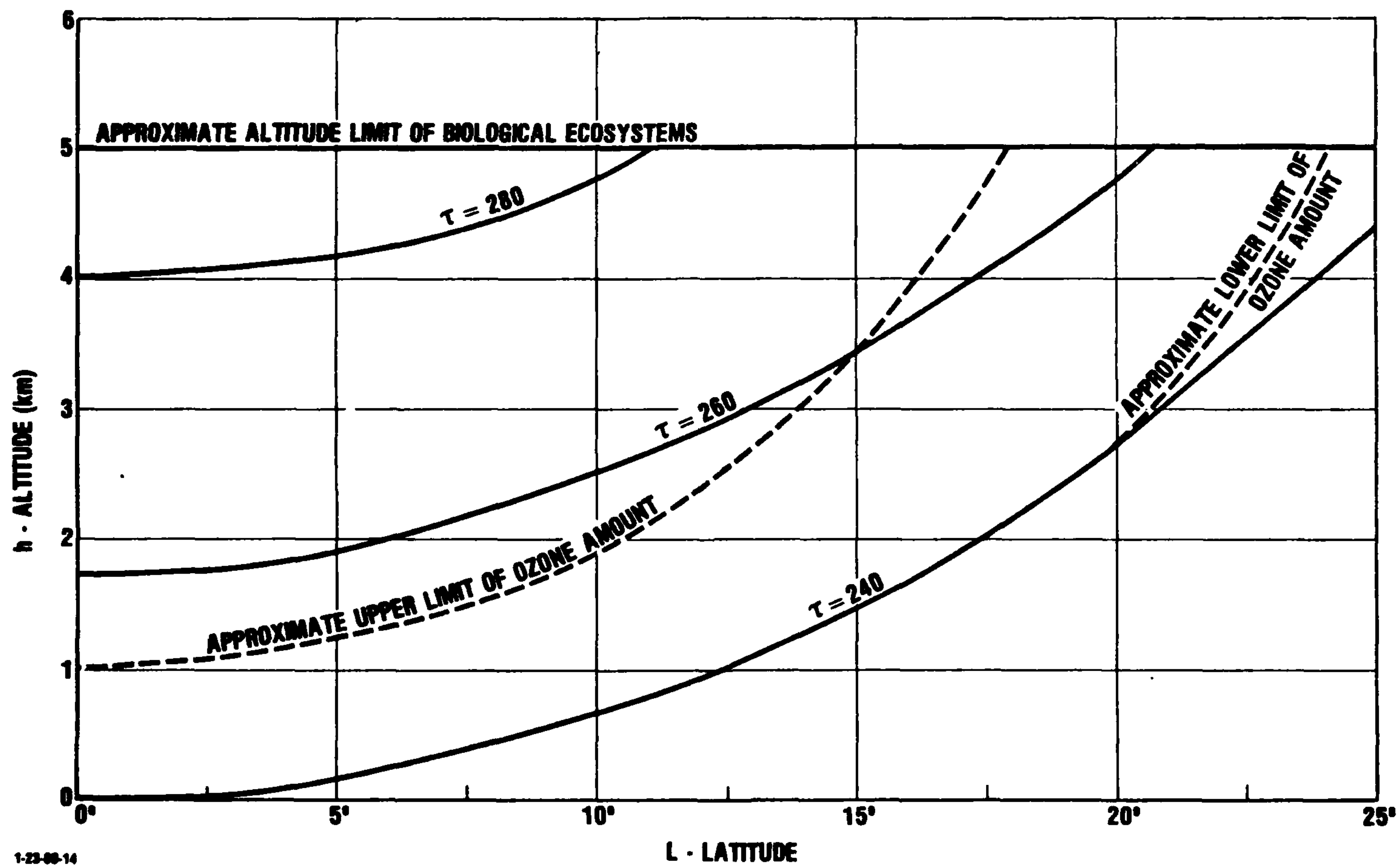

FIGURE 10. Site altitude and latitude required to match relative DUV of sea-level equatorial site of $\tau = 240$

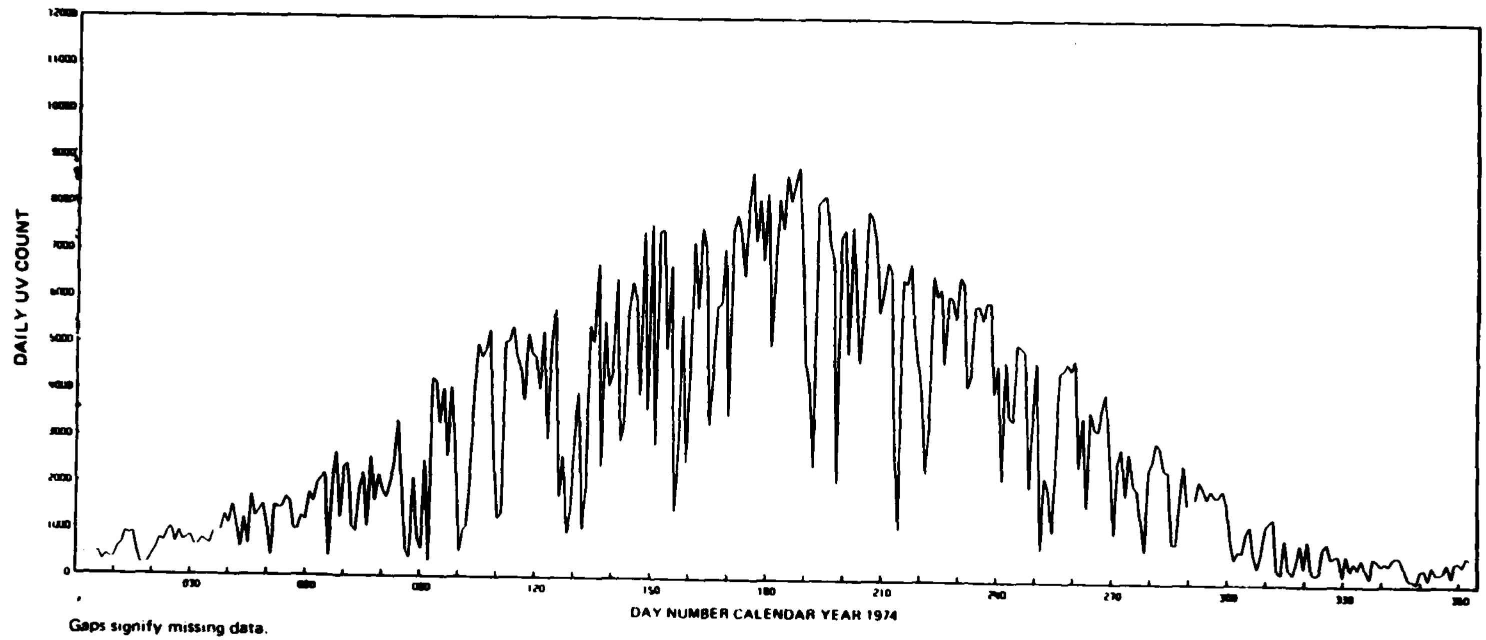

FIGURE 11. Daily total UV count for calendar year 1974, Minneapolis, Minnesota. (Source: Ref. 6)

demonstrated by the wild deviations from the envelope of the sine-like curve.* On August 3 the DUV dose was one-eighth of the clear-day dose (Ref. 6). The days when the DUV count fell on the envelope of the curve were clear days. By integrating the area of the curve under the envelope it is possible to calculate the value the Robertson-Berger meter would have measured had there been no clouds over the site for all 365 days in 1974. This integral is also tabulated in Table 1 as calculated from the curves, similar to Fig. 11, which are available for each of the 10 sites in Ref. 6. The ratio of the measured annual DUV value to the integral yields the desired cloudiness factor D_C. Note that in 1974 the value of D_C ranged from a low of 0.67 in Philadelphia to a high of 0.90 in Albuquerque.

TABLE 1. CLOUD FACTOR FOR 10 U.S. SITES IN 1974

AREA	LATITUDE (^oN)	ANNUAL DUV COUNT x 10^{-6}	$\int^*$	D_C
Mauna Loa, HI	19.5	2.77	3.24	0.85
Tallahassee, FL	30.4	1.66	2.16	0.77
El Paso, TX	31.8	2.24	2.52	0.89
Fort Worth, TX	32.8	1.61	2.20	0.73
Albuquerque, NM	35.1	1.89	2.10	0.90
Oakland, CA	37.7	1.51	1.83	0.83
Philadelphia, PA	39.9	1.11	1.65	0.67
Des Moines, IA	41.5	1.25	1.75	0.72
Minneapolis, MN	44.9	1.07	1.53	0.70
Bismarck, ND	46.8	1.13	1.64	0.69

*Annual DUV count with no clouds.

*Only a very small fraction of the deviations can be attributed to daily ozone thickness variations.

A comparison of frequency of cloudiness by cloud amount for the year 1974, the same year as that represented by the data in Table 1, is available for two of the sites in Table 1 (Fort Worth and Minneapolis) from calculations made by R. Penndorf (Ref. 7) and is reproduced in Table 2.

TABLE 2. COMPARISON OF CLOUDINESS IN FORT WORTH AND MINNEAPOLIS

	PERCENTAGE OF OCCURRENCES	
CLOUD AMOUNT	FORT WORTH	MINNEAPOLIS
0.0 - 0.1	38	30
0.2 - 0.8	16	10
0.9 - 1.0	46	60

A linear relationship of the relative DUV factor with cloudiness was found by K. Büttner in 1938 (Ref. 8). As indicated in Fig. 12, the cloudiness factor D_C can be well approximated by the linear equation

$$D_C = 1 - 0.55\ C\ , \tag{14}$$

where C is the average cloud amount (unity for a complete overcast).

With the more accurate data of Tables 1 and 2 (there were no DUV meters in 1938) it is now possible to check on the validity of Eq. (14).

If C_1 is defined as the average cloud amount for the range of cloud amount 0.0 - 0.1, i.e., 0.05*, C_2 for the range 0.2 - 0.8, i.e., 0.5, and C_3 for the range 0.9 - 1.0, i.e.,0.95, then the average cloud amount for the year may be represented by

$$C = \sum_{i=1}^{i=3} C_i\ P_i \tag{15}$$

*Assumes a uniform probability distribution over the cloud amount interval.

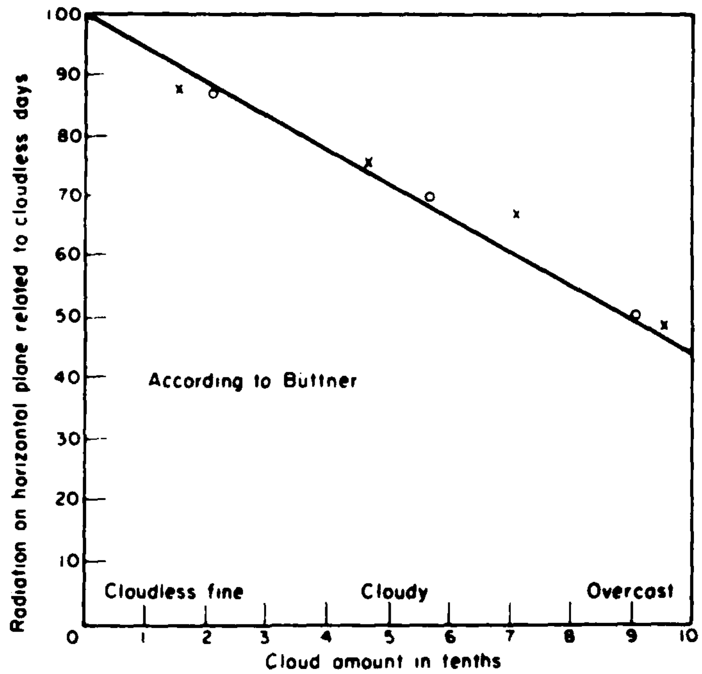

FIGURE 12. Dependence of relative intensity of UV-B total solar radiation on cloudiness. (Source: Ref. 8)

where p_i is the frequency of occurrence associated with average cloud amount C_i as given by the values in Table 2.

If γ is defined to be the coefficient of C in Eq. (14), then the relative cloudiness factor for Fort Worth, using the data in Tables 1 and 2 and Eq. (15), is given by

$$0.73 = 1 - \gamma\ [0.38 \times 0.05 + 0.16 \times 0.5 + 0.46 \times 0.95] \tag{16}$$

and for Minneapolis by

$$0.70 = 1 - \gamma\ [0.30 \times 0.05 + 0.10 \times 0.5 + 0.60 \times 0.95]\ . \tag{17}$$

Solutions of Eqs. 16 and 17 yield $\gamma = 0.50$ for Fort Worth and $\gamma = 0.47$ for Minneapolis. Both values are lower than the 0.55 value of Büttner, but a value of 0.50 is in good agreement with the straight line that Büttner could have drawn to better fit the points shown in Fig. 9 (note that two of his data points lie below his line and five lie above). Thus, the cloudiness factor adopted here is given simply by

$$D_C = 1 - 0.50\ C \quad . \tag{18}$$

A 10 percent error of 0.05 in the coefficient γ would result in an error of only 1.5 percent in D_C for a typical C value of 0.25. Since Eq. (18) was derived from data at mid-latitude sites, it is possible that a slightly different coefficient for C would be found for tropical sites.

There is a practical difficulty in applying Eq. (18) to compare relative DUV of low-latitude sites. Cloudiness data in the form given in Table 2 for Minneapolis and Fort Worth are not readily available. Photographs taken by meteorological satellites have been used to compile global charts of relative cloud cover (Ref. 9). These charts were considered not suitable for use in this paper because of the inability of the vidicon camera to distinguish cloud cover from snow cover, ice, and desert terrain, as well as inadequate resolution (40 km). Other global charts of mean cloudiness (e.g., *Handbook of Meteorology* by Berry, Bollay, and Beers, McGraw-Hill, 1945) are too crude for the purposes of this paper.

There exist other intractable meteorological factors that may be peculiar to a given site and significantly influence DUV. An example is the frequent morning fog over San Francisco. Experimental data on the effect of fog on relative DUV are not presently available.

E. GROUND ALBEDO

Another complex factor affecting relative DUV is the ground albedo. A site surrounded by snow-capped mountains will receive more ultraviolet radiation than one not surrounded by snowy terrain due to the high reflectivity of snow (Ref. 4). A snow surface may have a reflectivity ranging from 0.4 to 0.6 in the near UV (Ref. 3). Reflection of ultraviolet radiation from vegetation varies with the type of plant. The UV reflectance of a citrus upper-leaf surface is 4 percent, whereas the reflectance of the upper-leaf surface of a century plant is 6 percent (Ref. 10). Coastal sites will have different ground albedos than interior sites. Albedos for water surfaces are expected to be below 0.1 (Ref. 3). City sites will have different ground albedos than rural sites. Unfortunately, measurements of ground albedo in the ultraviolet for various types of terrain in equatorial regions (or for that matter almost anywhere else) are unavailable. Nonetheless, the effect of ground albedo on ultraviolet flux can be and has been investigated (Ref. 3).

In Fig. 13 is shown the effect of ground albedo on total flux for three ultraviolet wavelengths (300.4, 311.4, and 339.8 nm) and three different values of ground albedo (0.2, 0.4, and 0.6) as function of ozone amount for a sea-level site.

In Fig. 14 the effect of ground albedo, A, on relative DUV is shown for the wavelengths and ozone amounts of interest in the tropics. Evidently, the narrowness of the bands of interest results in a dependency which is essentially independent of λ and τ can be well represented by the relationship

$$D_A = 1 + 0.50\ A \qquad (19)$$

for expected average values of $A < 0.3$. It is a curious coincidence that in Eq. (19) the ground albedo, A, has the same coefficient as the average cloud amount, C, in Eq. (18), except for sign.

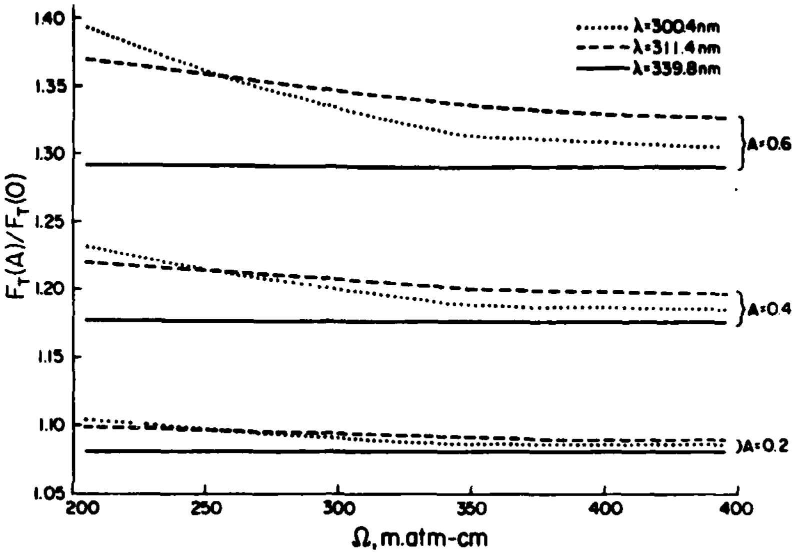

FIGURE 13. The effect of ground albedo (A) on the total flux (F_T) for three different wavelengths. The fluxes for three albedos are shown normalized to the zero albedo values, as the ozone amount (Ω) over a sea-level station is varied. (Source: Ref. 3)

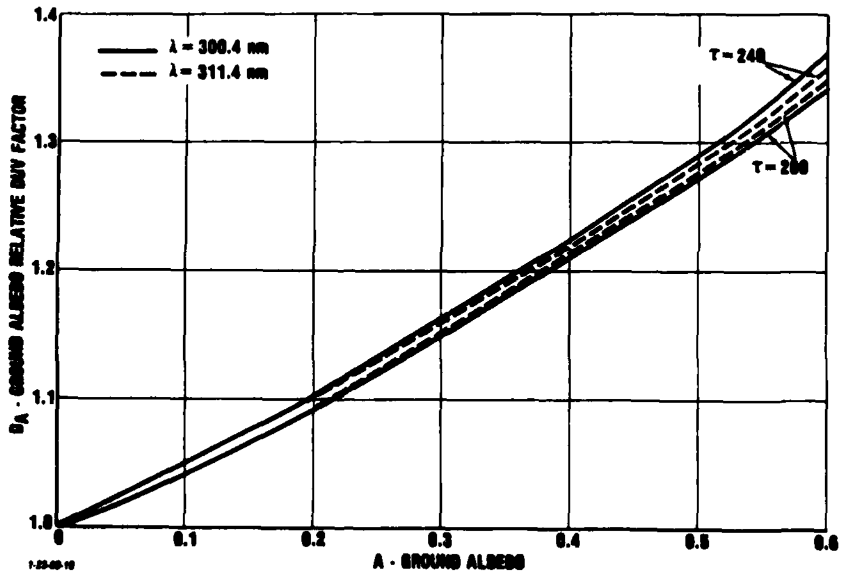

FIGURE 14. Effect of ground albedo on ultraviolet flux

Because of the flatness of the curves in Fig. 13 for A = 0.2, it can be seen that Eq. (19) is also a fairly good approximation for mid-latitude sites where τ values exceed 280 m. atm-cm.

F. AEROSOLS

The effect of aerosols on relative DUV suffers from the same complexity difficulties as cloudiness and ground albedo, depending on the shape, size, and size distribution of the particles, their altitude distribution, and their index of refraction, as well as the obviously important particle density (Ref. 3). The effect of aerosols on the radiation field can therefore only be calculated for particular models.

The model used by A.E.S. Green and T. Mo (Ref. 11) involved a standard amount of aerosols, on which their calculations were based. Calculations were made for 0, 1, 2, and 4 times the standard aerosols as indicated in the DUV curves of Fig. 15 for a latitude of 30°. Note that the DUV curves vary essentially linearly with amount of aerosols between the standard amount (1) curve and the 4-times-standard-amount curve. It follows that the effect of aerosols on relative DUV can therefore be represented approximately by the simple expression

$$D_\beta = 1 - 0.093\ (\beta - 1), \qquad (20)$$

where β is the ratio of the amount of aerosols at a site to the standard amount of aerosols. Equation (20) is normalized to a value of unity for $\beta = 1$. A 10 percent increase in the amount of aerosols above the standard amount would therefore correspond to a 1 percent reduction in the relative DUV, assuming the other five factors were held constant. Since relative differences of amount of aerosols over near-equatorial sites, where industrial sources of atmospheric pollution are relatively rare, can be expected to be small, it seems highly likely that the aerosol relative DUV factor is the least significant of the six factors

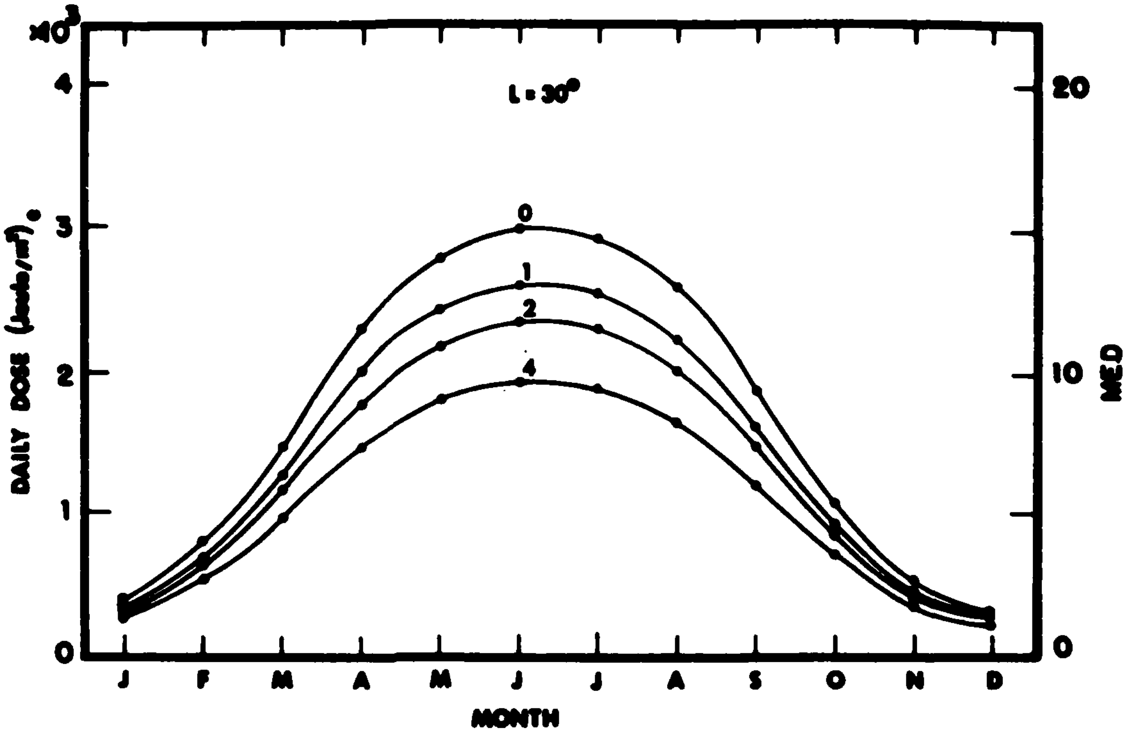

FIGURE 15. Daily erythema doses with four assumed amounts of aerosols. Amounts of aerosols are 0, 1, 2, and 4 times the standard aerosols and are labeled on the curves. One MED (minimum erythemal dose) is assumed to be 200 $(J/m^2)_e$. (Source: Ref. 11)

considered for the tropics. This is supported by the calculations for four U.S. cities (Fig. 16) comparing DUV with available turbidity data and standard aerosols (Ref. 2). Note that the effect of aerosols at mid-latitude sites is greatest in the summer months, and is minor for the small cities of Boulder, Colorado, and Tucson, Arizona, compared to the large cities of Los Angeles and Chicago.

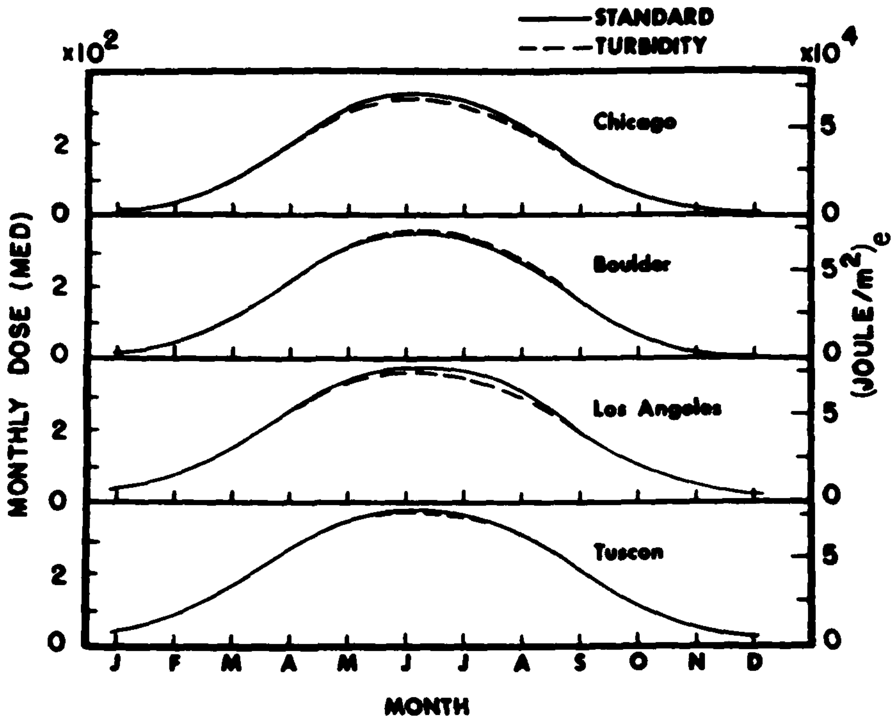

FIGURE 16. Calculation of the UV monthly erythema doses for four metropolitan areas with the data of local turbidity incorporated. Also shown are the results obtained with standard aerosols (solid curves). One MED is assumed to be 200 $(J/m^2)_e$. (Source: Ref. 2)

G. FORMULA FOR RELATIVE ANNUAL DUV AT TROPICAL SITES

Substituting Eqs. 13, 18, 19, and 20 in Eq. (1) gives, for the relative annual DUV at tropical sites, the formula

$$D = [1 - 0.00484\ (\tau - 240)]\ (1 + 0.06\ h)\ e^{-3.74 \times 10^{-4} L^2}$$

$$\times\ (1 - 0.50\ C)(1 + 0.50\ A)\ [1 - 0.093\ (\beta - 1)]\ , \qquad (21)$$

where

τ = amount of ozone in m. atm-cm

h = altitude of site in km

L = latitude of site in degrees

C = average cloud amount (unity for complete overcast)

A = ground albedo

β = ratio of amount of aerosols to standard amount of aerosols.

Eq. (21) can be used without much loss of accuracy for subtropical sites but for latitudes greater than 30° the more complex mid-latitude formula Eq. (44) is required.

H. RELATIVE ANNUAL DUV AT TROPICAL SITES

A comparison of calculated relative annual DUV is given in Table 3 for 19 selected tropical sites. Only the factors for which appropriate data is available were included in this comparison, i.e., D_τ, D_L, and D_h. The sites are listed in order of longitude following a westwardly direction. Values of τ were interpolated to the nearest 5 m. atm-cm from the τ contours in Fig. 1. Selection of the sites was made initially from crude topographic maps. Exact site elevation values were obtained from the Encyclopedia Britannica.

The highest h value for an inhabited site was found in Cerro de Pasco, Peru, a mining town of 5,720 people (1961) living at an altitude of 14,436 ft or 4.40 km. The calculated relative DUV value of 1.19 for Cerro de Pasco was the highest of the 19 selected sites, even though it was located 8° south of the equator. The second highest D value of 1.17 was found in Quito, Ecuador which has the relatively modest altitude of 2.85 km but lies on the equator. These high-altitude sites were found to have a relative DUV value approximately 80 percent higher than Key West, Florida.

The simple model of relative DUV for tropical sites derived in this paper can be used to tentatively identify interesting sites for the installation of DUV measuring instruments. Site selection would also depend on ecological considerations such as vegetation, human habitation, animal life, etc. Ideally, the selection of such sites should not be made until cloud cover statistics are available for the site candidates. No attempt to rank order the 19 sites of Table 3 by DUV was made because of the recognition that cloud-cover statistics, had they been available and included, would almost certainly have altered such a ranking.

TABLE 3. RELATIVE ANNUAL DUV DOSE AT SELECTED TROPICAL SITES

SITE	LONGITUDE	LATITUDE	τ(m.atm-cm)	h(km)	D_τ	D_L	D_h	D
Entebbe, Uganda	32½°W	0°	240	1.15	1.00	1.00	1.07	1.07
Nairobi, Kenya	37°W	2°S	240	1.68	1.00	1.00	1.10	1.10
Recife, Brazil	35°E	8°S	240	0	1.00	0.98	1.00	0.98
Caracas, Venezuela	67°E	10°N	245	0.91	0.98	0.96	1.05	0.99
La Paz, Bolivia	68°E	16°S	255	3.66	0.93	0.91	1.22	1.03
Oruro, Bolivia	67°E	18°S	255	3.71	0.93	0.89	1.22	1.01
Cuzco, Peru	72°E	13½°S	250	3.35	0.95	0.93	1.20	1.06
Bogota, Columbia	74°E	6½°S	245	2.61	0.98	0.98	1.16	1.11
Huancayo, Peru	75°E	12°S	250	3.26	0.95	0.95	1.20	1.08
Cerro de Pasco, Peru	76°E	10°S	245	4.40	0.98	0.96	1.26	1.19
Lima, Peru	77°E	12°S	250	0.15	0.95	0.95	1.01	0.91
Quito, Ecuador	78½°E	0°	240	2.85	1.00	1.00	1.17	1.17
Panama Canal Zone	79½°E	9°N	240	0	1.00	0.97	1.00	0.97
Key West, Florida	82°E	24½°N	275	0	0.83	0.80	1.00	0.66
Mauna Loa, Hawaii	156°W	19°N	260	4.00	0.90	0.87	1.24	0.97
Townsville, Australia	147°W	19°S	260	0	0.90	0.87	1.00	0.78
Saigon, Vietnam	107°W	9°S	255	0	0.93	0.97	1.00	0.90
Singapore	104°W	2°N	250	0	0.95	1.00	1.00	0.95
Bangalore, India	77½°W	13°N	250	0.95	0.95	0.94	1.06	0.95

III. MID-LATITUDE SITES

A. DUV VS OZONE THICKNESS AT THE EQUATOR

To derive a formula for relative DUV for mid-latitude sites, it is first necessary to modify Eq. (4) for the ozone thickness factor D_τ. The latter covered only the tropical range of ozone values 240-280 m. atm-cm. Since τ values can reach as high as 400 m. atm-cm in the Northern Hemisphere, it is necessary to derive another formula for D_τ for application to mid-latitude sites.

In Fig. 17 is shown the annual relative DUV at the equator as a function of ozone thickness τ. The solid line is drawn through the circled points which are based on calculations of A.E.S. Green and T. Mo (Ref. 11). The relative DUV units in Fig. 17 are based on daily erythema doses on the 15th day of each month in $(\text{Joules/m}^2)e$ and differ from those in Fig. 4 which were based on annual monthly sums in MED.

A very good parabolic approximation, obtained by fitting the calculated DUV values at 300, 350, and 400 m. atm-cm, is given by

$$D_\tau = 3.80 \times 10^{-5}\,\tau^2 - 3.95 \times 10^{-2}\,\tau + 11.19\ . \qquad (22)$$

In order that Eq. (22) be compatible with Eq. (4), the equations are matched at $\tau = 250$. According to Eq. (4), $D_\tau = 0.9516$ at $\tau = 250$, whereas, according to Eq. (22), $D_\tau = 3.69$. Thus, multiplying Eq. (22) by 0.9516/3.69 yields the normalized parabolic approximation

$$D_\tau = 9.80 \times 10^{-6}\,\tau^2 - 1.0186 \times 10^{-2}\,\tau + 2.886\ . \qquad (23)$$

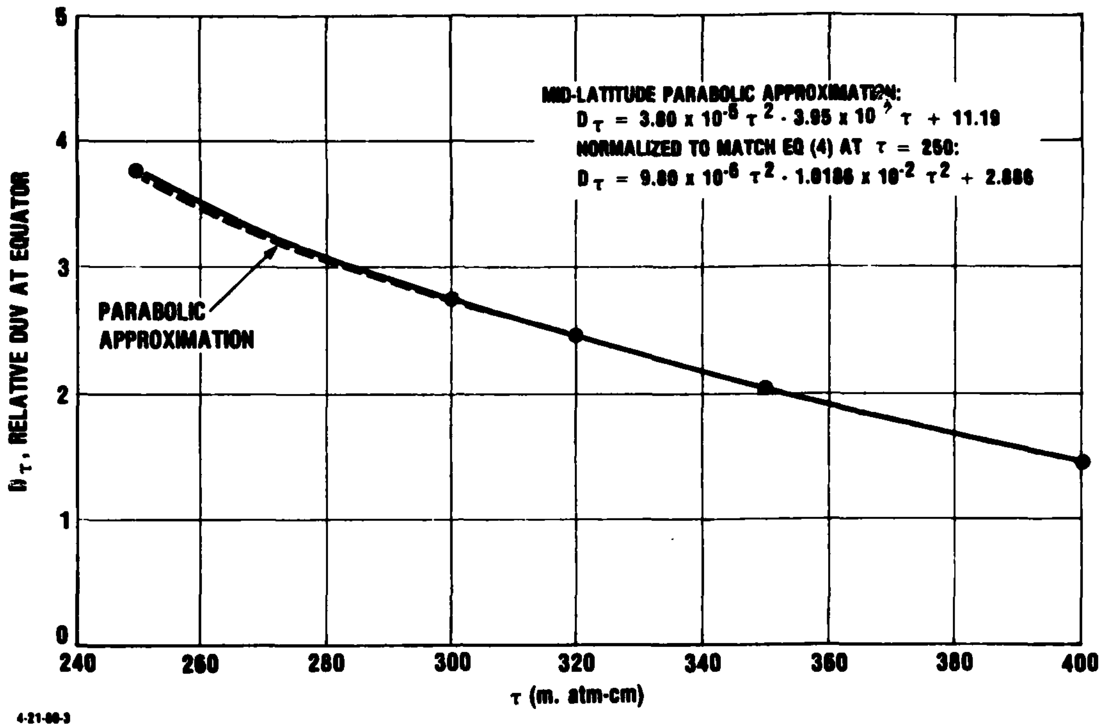

FIGURE 17. Relative DUV at equator vs ozone thickness

B. MID-LATITUDE CORRECTION FOR TROPICAL LATITUDE FACTOR

The tropical latitude exponential factor D_L in Eq. (5) must be modified for mid-latitude application. If D_{Lm} (τ, L) denotes the mid-latitude relative annual DUV for ozone thickness τ and latitude L, and α (τ, L) denotes the correction factor for the value of D_L as given by Eq. (5), then

$$D_{Lm}(\tau, L) = \left[1 - \alpha(\tau, L)\right] D_L \tag{24}$$

$$= \left[1 - \alpha(\tau, L)\right] e^{-3.74 \times 10^{-4} L^2} . \tag{25}$$

In Fig. 18 are shown the results of calculations of α (τ, L) based on tables in Refs. 2 and 11 for τ values of 256, 300, 320, 350, and 400 m. atm-cm and L values of 30°, 35°, 40°, 45°, 50°, and 55°. According to Fig. 1, the α values of interest will lie

between the two dashed lines in Fig. 18. It is seen that for a given latitude, α is empirically found to be a linear function of τ. The slopes of the lines in Fig. 18 are seen to increase with latitude. If f (L) denotes the correction factor for τ = 256 m. atm-cm, and S (L) denotes the slope as a function of latitude, then the correction factor α (τ, L) is given by

$$\alpha\ (\tau,\ L) = f\ (L) + (\tau - 256)\ S\ (L)\quad . \qquad (26)$$

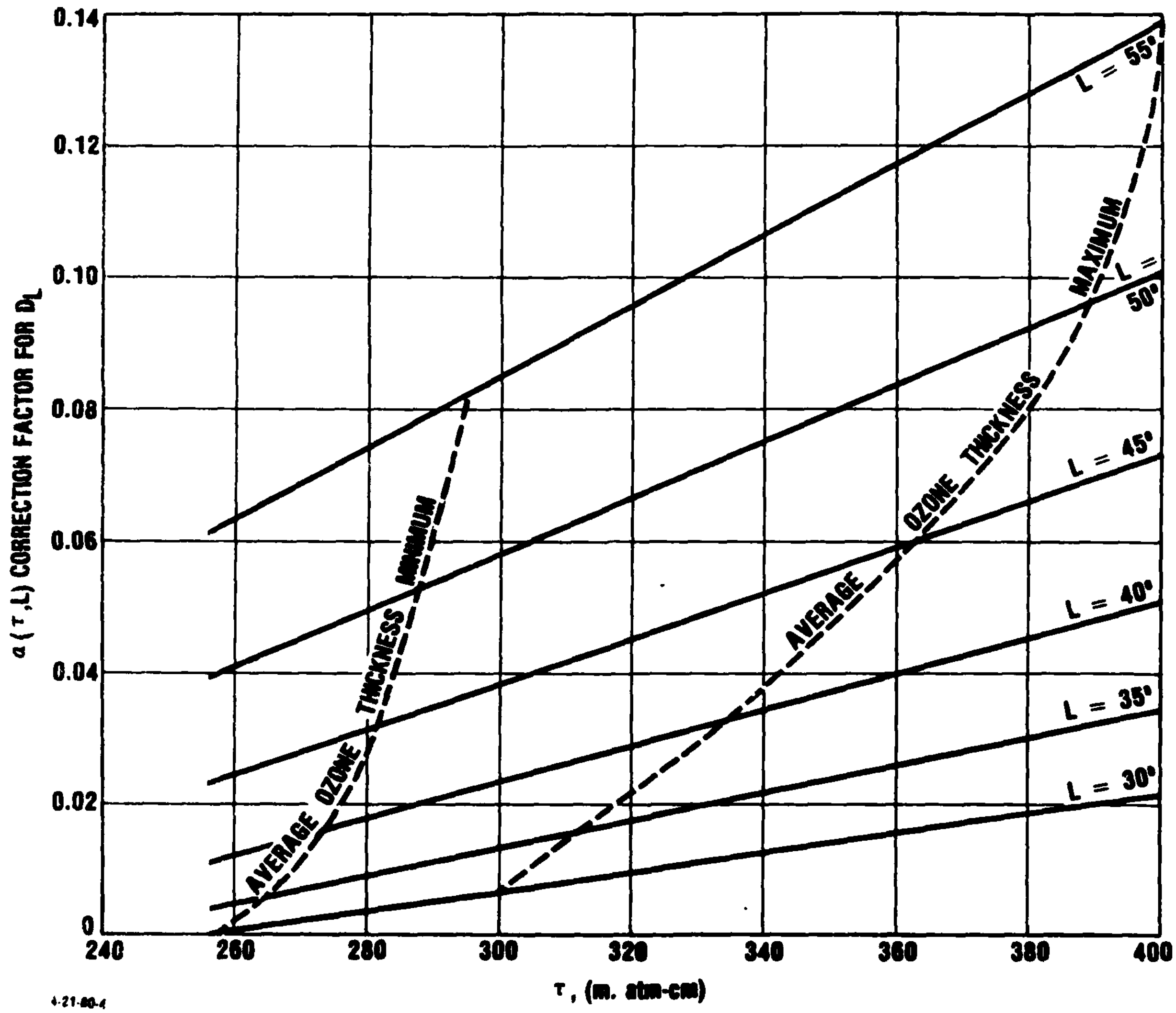

FIGURE 18. Correction factor for D_L

By fitting the values of α (τ, L) at τ = 256 m. atm-cm for latitudes 30°, 45°, and 55° to a parabola, it is found that a good approximation for f (L), as illustrated in Fig. 19, is given by

$$f\ (L) = 9.08 \times 10^{-5}\ L^2 - 5.28 \times 10^{-3}\ L^2 + 7.67 \times 10^{-2}\ . \quad (27)$$

The slope S (L) is found to be linear in the interval 30° < L < 45°, as indicated in Fig. 20. The function S (L) may be approximated by the equation

$$S\ (L) = g\ (L) + \delta\ \mu\ (L)\ , \quad (28)$$

where δ = 0 for the interval 30° < L < 40° and δ = 1 for L > 45°; μ (L) is a slope correction factor for latitudes greater than 45°. By assuming the slope correction factor μ (L) increases proportionally to the square of (L - 45°), the function S (L) is well approximated by the equation

$$S\ (L) = 1.46 \times 10^{-4} + 1.34 \times 10^{-5}\ (L - 30°)$$
$$+ 6.10 \times 10^{-7}\ \delta\ (L - 45)^2\ . \quad (29)$$

Substituting Eqs. (27) and (29) in Eq. (26), the mid-latitude correction factor α (τ, L) is therefore given by

$$\alpha\ (\tau,\ L) = 9.08 \times 10^{-5}\ L^2 - 5.28 \times 10^{-3}\ L^2 + 7.67 \times 10^{-2}$$
$$+ (\tau - 256)\ \Big[1.46 \times 10^{-4} + 1.34 \times 10^{-5}\ (L - 30°)$$
$$+ 6.10 \times 10^{-7}\ \delta\ (L - 45°)^2\Big]\ , \quad (30)$$

where δ = 0 for the interval 30° < L < 45° and δ = 1 for L > 45°.

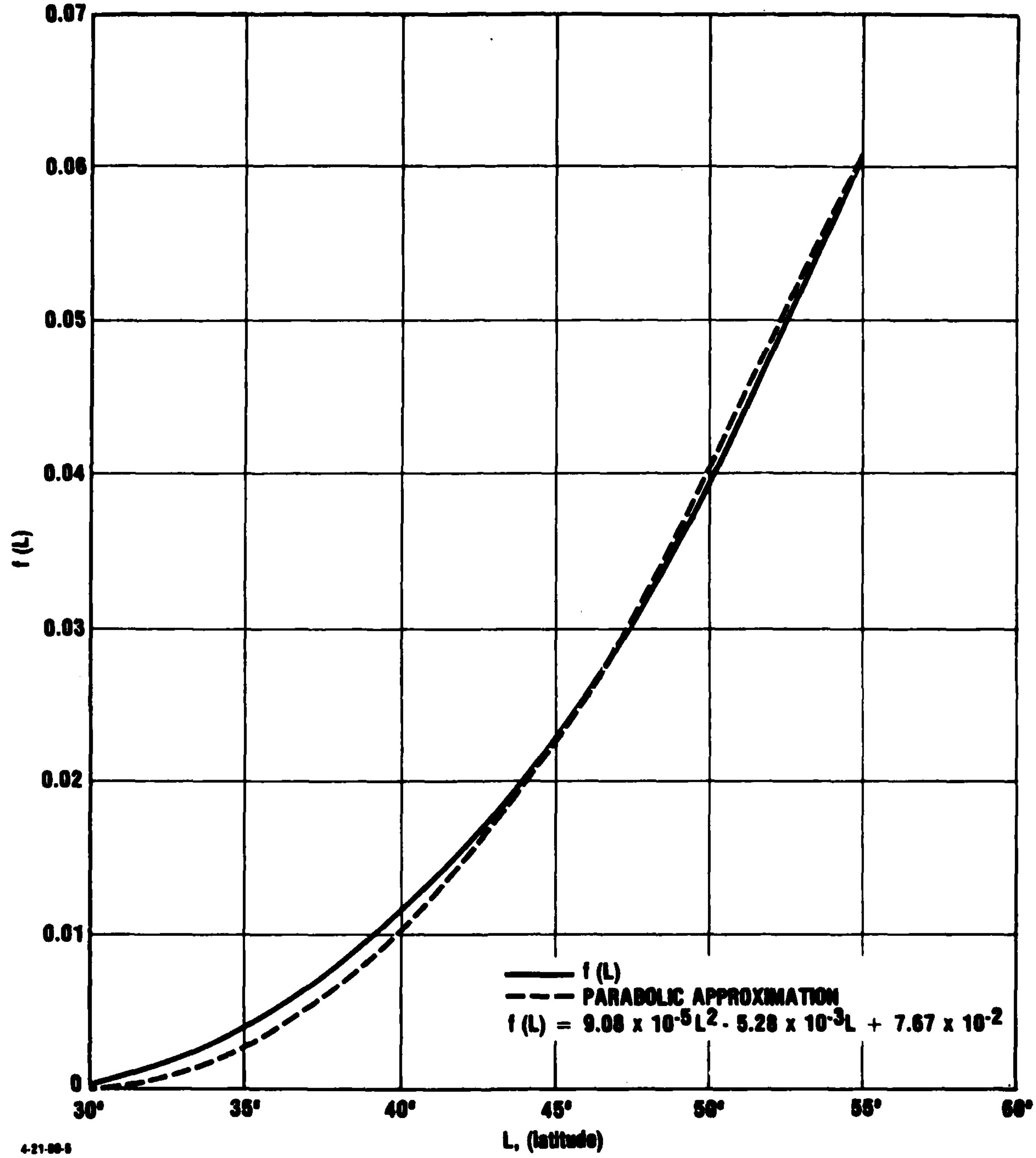

FIGURE 19. f(L) and a parabolic approximation

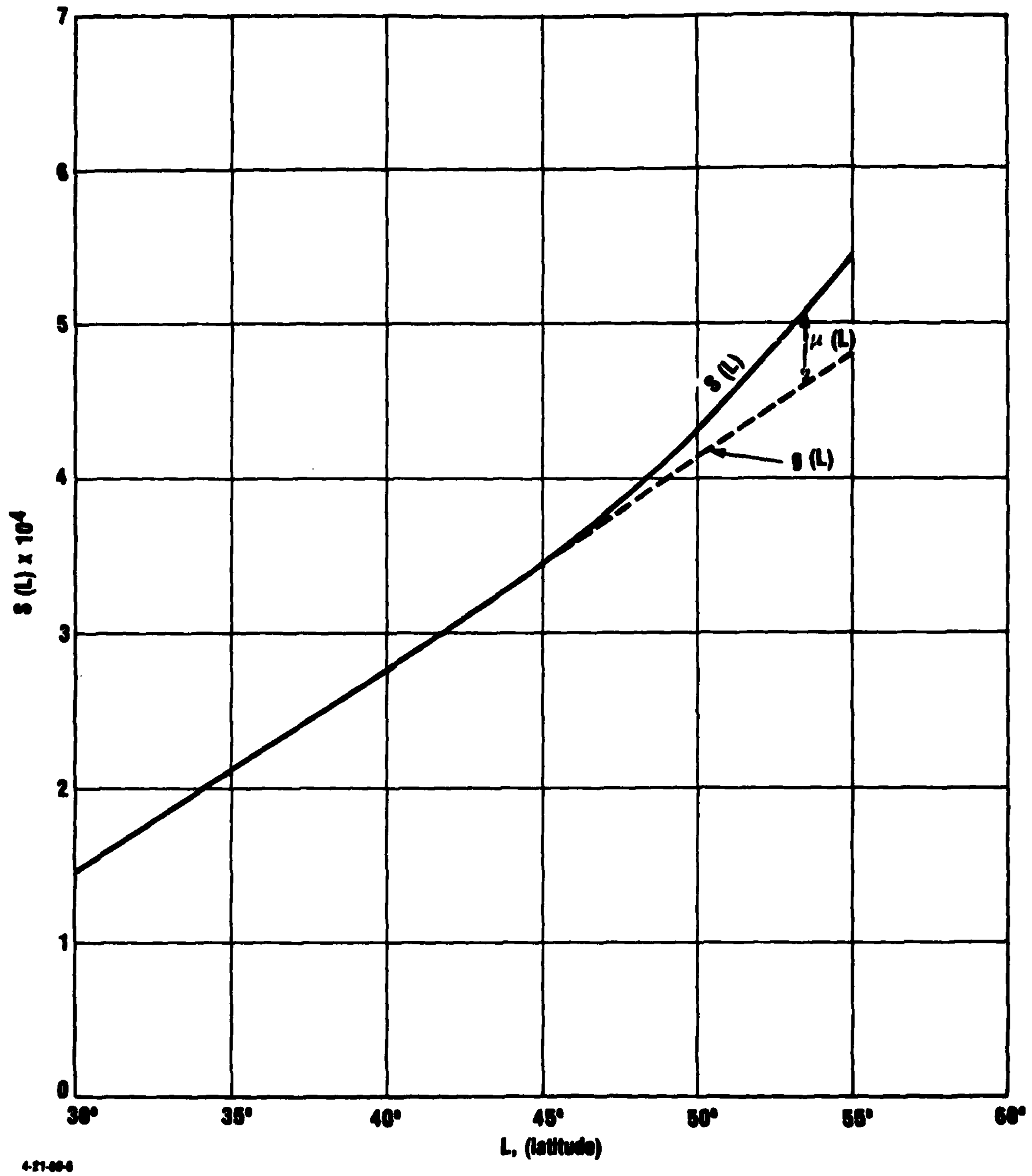

FIGURE 20. S(L) vs L

C. CORRECTION FACTOR FOR SEASONAL OZONE VARIATION

If the average ozone thickness were a constant value independent of season, then the substitutions of Eq. (23) for the ozone thickness factor D_τ and Eqs. (25) and (30) for the latitude factor D_L in the tropical relative DUV formula of Eq. (5) would accurately estimate the relative DUV for a mid-latitude site. However, the ozone thickness varies significantly from month to month at mid-latitude sites. This seasonal ozone variation introduces a significant fractional error ρ such that

$$D_s = D\left[1 + \rho\ (\tau,\ L)\right] , \tag{31}$$

where D_s is the relative annual DUV as adjusted for seasonal ozone variation. It will be shown below that ρ is positive in the Northern Hemisphere and negative in the Southern Hemisphere. It will also be shown that ρ is a function of the average annual ozone thickness, τ, as well as latitude, L, in the Northern Hemisphere, but appears to be essentially independent of τ in the Southern Hemisphere.

In the global ozone distribution atlas of Ref. 1, ozone thickness is tabulated for each month of the year between July 1957 and June 1967, for 5° latitude intervals in the Northern and Southern Hemispheres, and for 20° longitude intervals in both hemispheres. For a given geographic location, let the tabulated entry τ_{ij} denote the ozone thickness during the j^{th} month of the i^{th} year. The ten-year average ozone thickness for the j^{th} month is then given by

$$\tau_j = \frac{1}{10} \sum_{i=1}^{i=10} \tau_{ij} \tag{32}$$

and the average annual ozone thickness by

$$\tau = \frac{1}{12} \sum_{j=1}^{j=12} \tau_j \ . \tag{33}$$

The average annual relative DUV dose D can be accurately calculated by summing the monthly relative DUV dose using the appropriate monthly value of ozone thickness, τ_{ij}, i.e.,

$$D_s = \sum_{j=1}^{j=12} D_j \ (\tau_j) \ . \tag{34}$$

An approximate calculation for relative annual DUV dose can also be obtained by using the average annual ozone thickness, τ, from Eq. (33) for each month of the year, i.e.,

$$D = \sum_{j=1}^{j=12} D_j \ (\tau) \ . \tag{35}$$

The approximate form Eq. (35) is the one that was used in the tropical relative DUV formula and was based on the tabulated monthly values given in the tables of Refs. 2 and 11. The fractional error ρ that results if seasonal ozone variation is neglected and Eq. (35) is used for mid-latitude sites is given by

$$\rho = \frac{D_s}{D} - 1 \ . \tag{36}$$

To investigate the behavior of ρ with latitude and ozone thickness, calculations for D_s and D were made for six sites in the Northern Hemisphere and five sites in the Southern Hemisphere. The values of longitude and latitude, and the calculated values of τ and ρ for these eleven sites are given in Table 4. In Fig. 21 the values of ρ are plotted as a function of latitude. Note that in the Northern Hemisphere the value of

ρ is positive and is much greater at longitude 100°E than longitude 100°W, and increases with latitude at a faster rate. In the Southern Hemisphere, the value of ρ is negative and the values for longitude 60°E are very nearly the same as for longitude 60°W.

TABLE 4. τ AND ρ VALUES FOR ELEVEN SELECTED SITES

Latitude	Longitude	τ	ρ
25°S	60°W	271.1	-0.015
45°S	60°W	303.7	-0.033
55°S	60°W	313.7	-0.053
45°S	60°E	334.5	-0.036
55°S	60°E	339.7	-0.076
25°N	100°W	274.3	-0.015
45°N	100°W	351.6	0.030
55°N	100°W	379.4	0.060
25°N	100°E	259.3	-0.010
45°N	100°E	308.9	0.082
55°N	100°E	333.1	0.164

Insights into the complexity of the behavior of the seasonal ozone variation correction factor ρ can be gained from comparisons of the ten-year average monthly ozone thickness τ_j for the eleven sites in Figs. 22a through 22f. Observe the following:

1. In the Southern Hemisphere, a minimum value of τ_{ij} occurs at mid-latitudes in April and a maximum value in November; in the Northern Hemisphere, τ_{ij} is maximum in February to March and minimum in August to October.

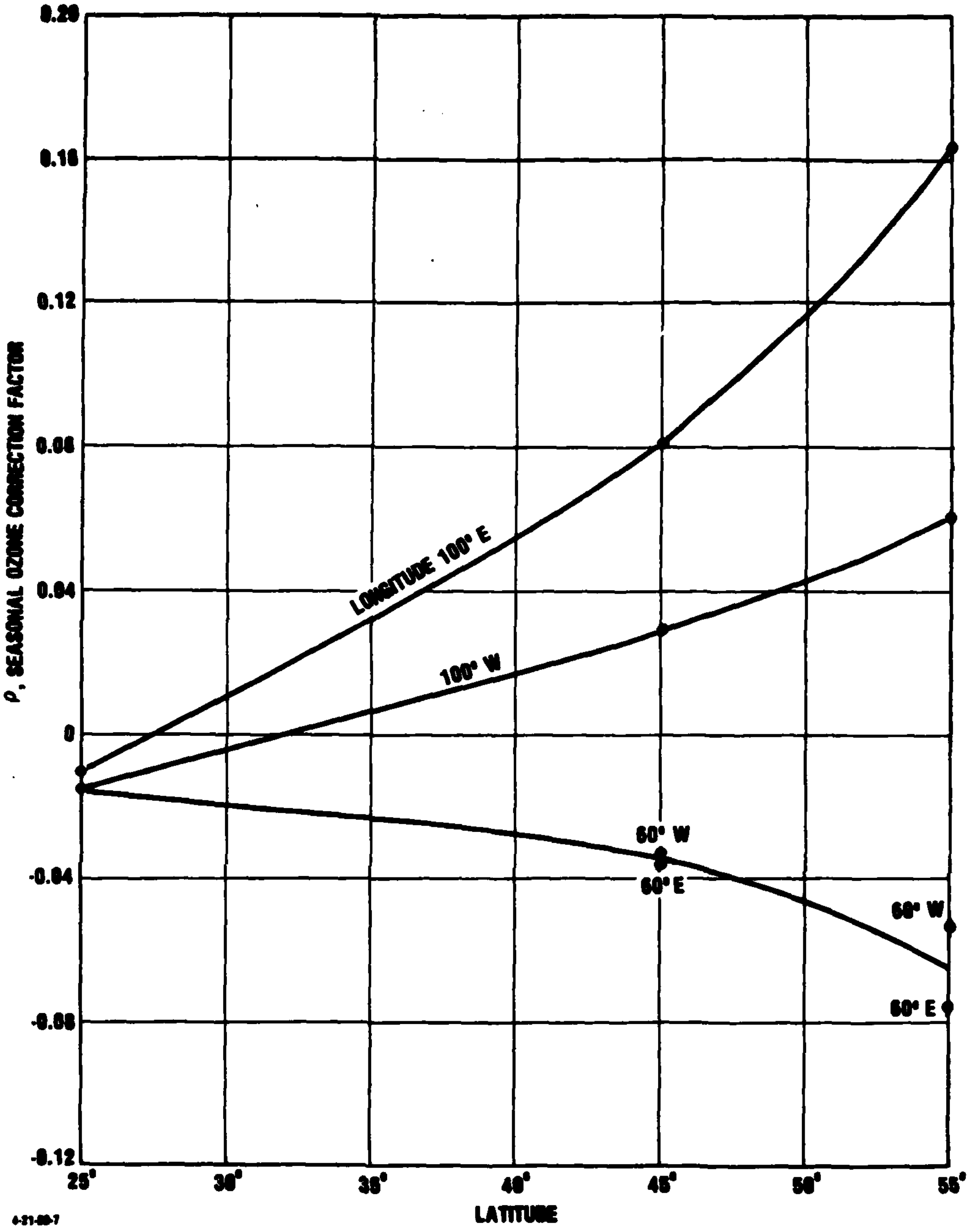

FIGURE 21. Seasonal ozone correction factor for relative DUV

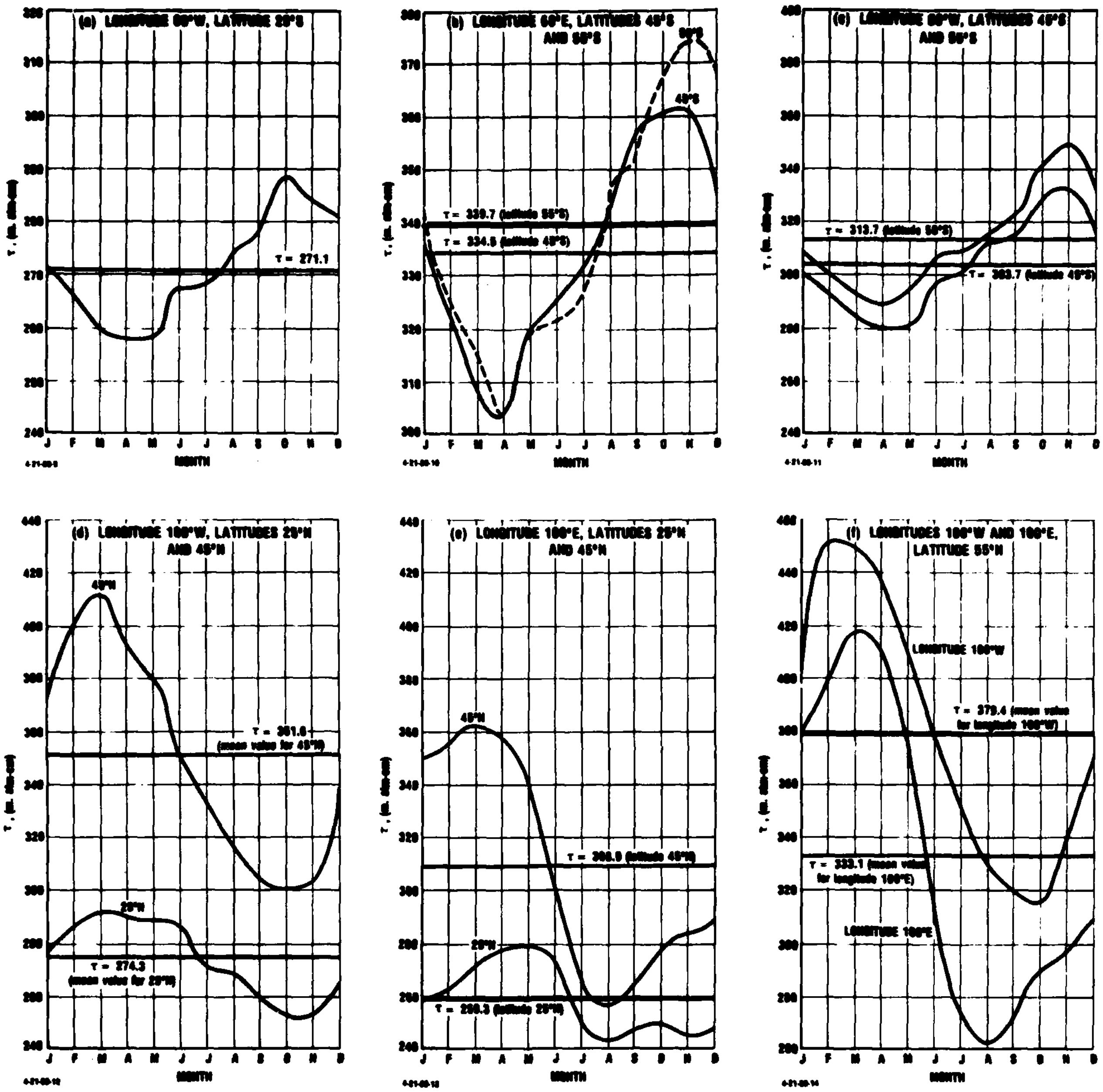

FIGURE 22. Seasonal variation of ten-year average ozone

2. The amplitude of the curve, i.e., the maximum value minus the minimum value, increases with increasing latitude, is much greater for the Northern than the Southern Hemisphere for a given latitude, and varies more with longitude in the Northern Hemisphere than in the Southern.

3. The curves are neither smooth nor symmetrical, indicating phase shifts, e.g., in Fig. 22f, differences in the period for which τ_j is greater than τ, and differences in the values of $|\tau_j - \tau|$ for the maximum and minimum values of τ_j (e.g., Fig. 22b).

Despite the irregularities in the seasonal ozone thickness curves, there is also much commonality in their characteristics, leading to fairly well-defined seasonal effects on the relative DUV calculations. In Fig. 23, the relative DUV on the 15th day of each month is plotted for each month of the year with seasonal ozone variation, i.e., D (τ_{ij}), and for a constant annual mean amount of ozone, i.e., D (τ), and for each of the five selected sites in the Southern Hemisphere; in Fig. 24 D (τ_{ij}) and D (τ) are shown for each of the six selected sites in the Northern Hemisphere.

The following conclusions can be drawn from the behavior of the D (τ_{ij}) and D (τ) curves in Figs. 23 and 24.

1. In the Southern Hemisphere, all of the D (τ_{ij}) and D (τ) curves reach a minimum value in June. However, and more importantly, the D (τ_{ij}) curves reach a maximum value in January, whereas the D (τ) curves reach a maximum value in December.

2. In the Northern Hemisphere, the D (τ_{ij}) are found to reach a maximum value in July, whereas D (τ), of course, always will reach a maximum value in June.

3. The symmetry of the D (τ) curves is not to be found in the D (τ_{ij}) curves, particularly in the Northern Hemisphere.

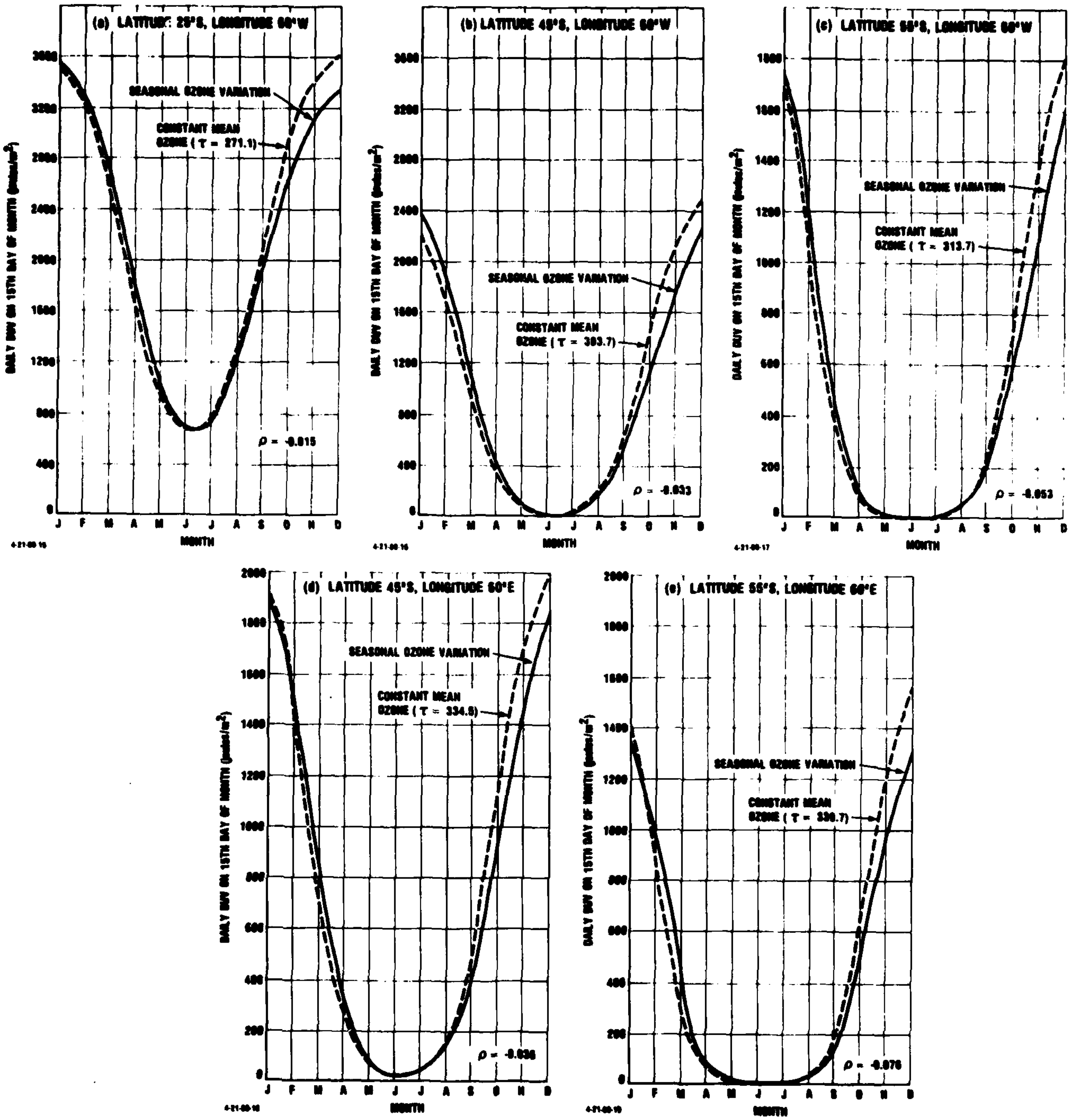

FIGURE 23. Comparison of daily DUV using seasonal ozone variation and using constant mean value of ozone for five sites in the Southern Hemisphere

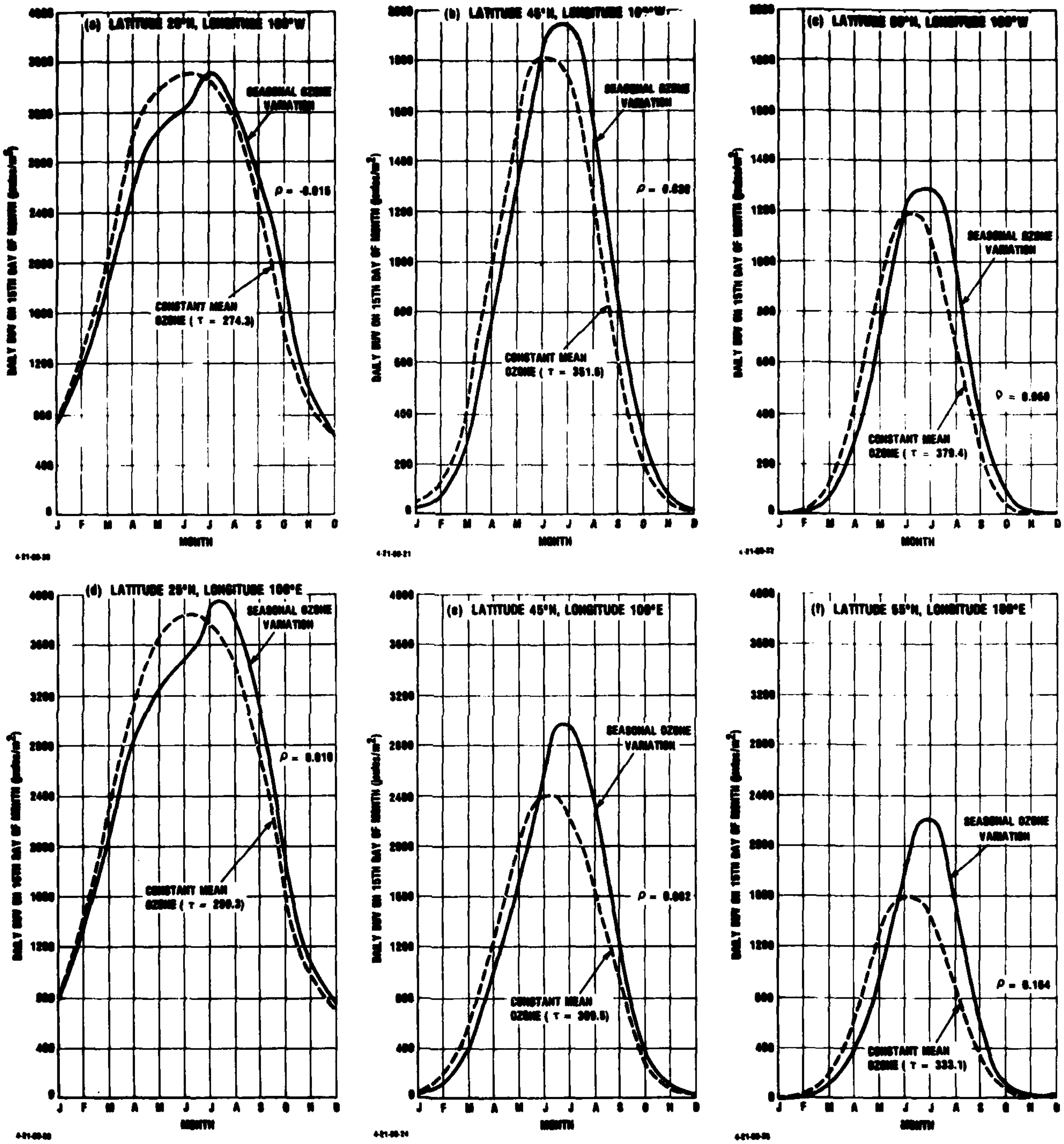

FIGURE 24. Comparison of daily DUV using seasonal ozone variation and using constant mean value of ozone for six sites in the Northern Hemisphere

4. In the Southern Hemisphere, from January to June, $D(\tau_{ij}) > D(\tau)$; from July to December, $D(\tau_{ij}) < D(\tau)$.

5. In the Northern Hemisphere, from January to May or June, $D(\tau_{ij}) < D(\tau)$; from June or July to December, $D(\tau_{ij}) > (\tau)$.

6. The values of ρ are not very large, because the difference in the $D(\tau_{ij})$ and $D(\tau)$ curves during the first half of the year is, to a large extent, negated by the difference in the two curves of opposite sign during the second half of the year.

For the Southern Hemisphere, it is possible to approximate ρ as a function of latitude with a single equation (Fig. 21). By using the mean value of ρ for longitudes 60°E and 60°W at latitudes 45°S and 55°S, a parabolic fit of ρ at latitudes 25°S, 45°S, and 55°S results in a seasonal ozone correction factor ρ_s for the Southern Hemisphere of

$$\rho_s(L) = -6.75 \times 10^{-5} L^2 + 3.75 \times 10^{-3} L - 6.66 \times 10^{-2}. \quad (37)$$

As can be seen from inspecting Fig. 1, longitude 60°W lies in a region of low values of τ at mid-latitudes, whereas longitude 60°E lies in a region of relatively high values. It would therefore appear to be the case that ρ_s is essentially independent of τ or the seasonal ozone fluctuations that tend to be highly correlated with τ.

In the Northern Hemisphere, the seasonal ozone correction factor ρ_n is strongly dependent on τ as well as L and so a more complex formulation is required.

The behavior of τ in the Northern Hemisphere with a change in longitude is shown in Fig. 25. Note that longitude 100°E, which at mid-latitude represents a region of minimum amount of ozone and seasonal ozone fluctuations is, surprisingly, a region

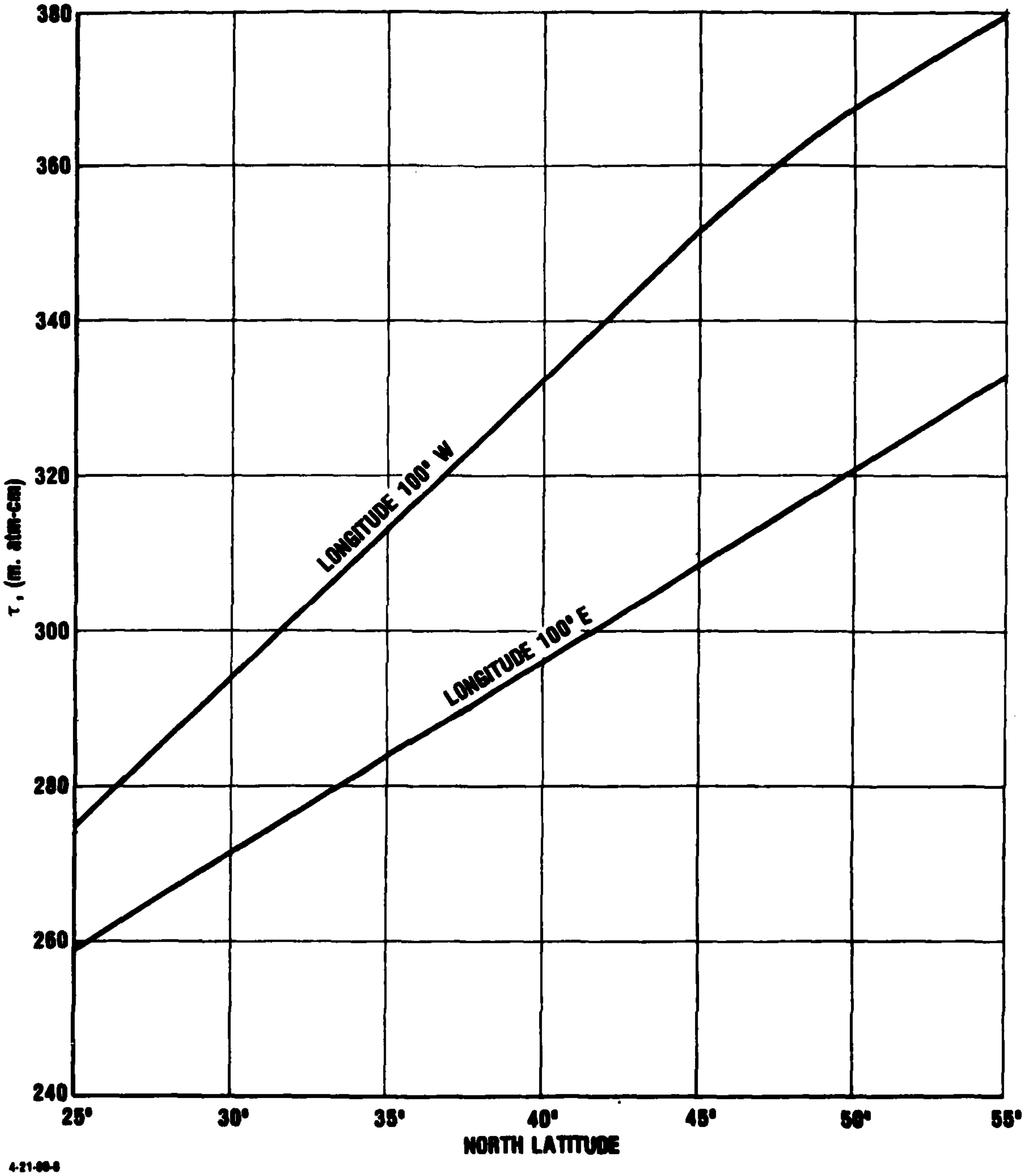

FIGURE 25. Mean annual ozone thickness vs latitude for longitudes 100°E and 100°W in the Northern Hemisphere

of maximum values of the seasonal ozone correction factor ρ (Fig. 21), whereas longitude 100°W, which represents a region of maximum amount of ozone and relatively large seasonal ozone fluctuations, is a region of minimum values of ρ. Let τ_o (L) represent the ozone thickness as a function of latitude for longitude 100°E. From Fig. 25 it is seen that τ_o (L) can be well approximated by the linear equation

$$\tau_o (L) = 197.8 + 2.46 L . \tag{38}$$

The equation ρ_o (L) for ρ at longitude 100°E in Fig. 21 can be approximated by fitting the values of ρ at latitudes 25°, 45°, and 55°. The result is

$$\rho_o (L) = 0.010 + 1.20 \times 10^{-4} L^2 - 3.80 \times 10^{-3} L . \tag{39}$$

The equation for ρ at a longitude between 100°E and 100°W, and hence a value of τ between the two curves in Fig. 25, can be approximated by the equation

$$\rho (\tau, L) = \rho_o (L) - [\tau - \tau_o (L)] q (L) \tag{40}$$

where q (L) is the difference in the ρ curves for longitudes 100°E and 100°W (Fig. 21) divided by the difference in the corresponding τ values (Fig. 25). Thus,

$$q (L) = \frac{\rho_o (L) - \rho_1 (L)}{\tau_1 (L) - \tau_o (L)} , \tag{41}$$

where ρ_1 (L) and τ_1 (L) are the seasonal ozone correction factor and ozone thickness, respectively, for longitude 100°W. By fitting a parabola to the latitude points 25°, 45°, and 55°, it can be shown that

$$q (L) = 1.424 \times 10^{-3} + 1.955 \times 10^{-6} L^2 - 9.25 \times 10^{-5} L. \tag{42}$$

Substituting Eqs. 38, 39, and 42 in Eq. 40 results in the following approximate formula for ρ in the Northern Hemisphere as a function of L and τ.

$$\rho_n\ (\tau,\ L) = 0.010 + 1.20 \times 10^{-4}\ L^2 - 3.80 \times 10^{-3}\ L - (\tau - 197.8 - 2.46\ L)\ (1.424 \times 10^{-3} + 1.955 \times 10^{-6}\ L^2 - 9.25 \times 10^{-5}\ L) \tag{43}$$

D. FORMULA FOR RELATIVE ANNUAL DUV AT MID-LATITUDE SITES

Substituting Eq. (23) for the first term in Eq. (21), multiplying by the latitude correction $[1 - \alpha\ (\tau,\ L)]$ and the seasonal ozone correction factor ρ gives, for the relative annual DUV at mid-latitude sites, the formula

$$D = (9.80 \times 10^{-6}\ \tau^2 - 1.0186 \times 10^{-2}\ \tau + 2.886) \times [1 - \alpha\ (\tau,\ L)]\ e^{-3.74 \times 10^{-4}\ L^2}\ [1 + \rho\ (\tau,\ L)]\ (1 + 0.06\ h) \times (1 - 0.50C)\ (1 + 0.50\ A)\ [1 - 0.093\ (\beta - 1)] \tag{44}$$

where $\alpha\ (\tau,\ L)$ is given in Eq. (30), and $\rho\ (\tau,\ L)$ by Eq. (37) for the Southern Hemisphere and by Eq. (43) for the Northern Hemisphere. Other symbols are as defined on p. 26.

IV. CONCLUSIONS

It is shown in this paper that it is possible to derive and apply, to the extent that available ozone and meteorological and geographical data are available, a formula for a relatively quick determination of annual relative DUV dose for tropical and mid-latitude sites. The input parameters required are average annual amount of ozone, latitude, altitude, average cloud amount, ground albedo, and amount of aerosols. Ozone, latitude, and altitude information is readily available. Cloudiness information to the accuracy required is, unfortunately, not readily available on a worldwide basis. Input data on ground albedo and aerosol content are also not readily available, but, in general, can be expected to play a less significant role than the other four parameters.

The derived formulas for tropical and mid-latitude sites can be used to provide a fundamental input parameter, relative annual DUV dose, in models designed to investigate the effects of solar ultraviolet radiation and its possible increase resulting from stratospheric ozone depletion, on ecological systems on land and in the oceans of the world, and on the incidence of skin cancer in white Caucasian populations.

Because of the sparsity of the data available and possible interdependency effects in the six multiplicative factors derived, the formula remains to be validated in a general sense.

REFERENCES

1. J. London, R. D. Bojkov, S. Oltmans, and J. I. Kelley, *Atlas of the Global Distribution of Total Ozone July 1957-June 1967*, National Center for Atmospheric Research, NCAR/TN/113 + STR, January 1976.

2. T. Mo and A. E. S. Green, *Systematics of Climatic Variables and Implications - Local Erythema Dose*, CIAP Monograph 5, Part 1, "Ultraviolet Radiation Effects," Chapter 2, Appendix K, Department of Transportation Climatic Assessment Program, September 1975.

3. S. V. Venkateswaren et al., *Radiation in the Natural and Perturbed Troposphere*, CIAP Monograph 4, Chapter 5, Department of Transportation Climatic Assessment Program, September 1975.

4. P. Cutchis, "Stratospheric Ozone Depletion and Solar Ultraviolet Radiation on Earth," *Science, 184*, 13, 1974.

5. D. F. Robertson, *Calculated Sunburn Responses*, CIAP Monograph 5, Part 1, Chapter 2, Appendix J, Department of Transportation Climatic Assessment Program, September 1975.

6. J. Scotto, T. R. Fears, and G. B. Gori, *Measurements of Ultraviolet Radiation in the United States and Comparison with Skin Cancer Data*, National Cancer Institute, DHEW No. (NIH) 76-1029.

7. P. Cutchis, *On the Linkage of Solar Ultraviolet Radiation to Skin Cancer*, IDA PAPER P-1342, Institute for Defense Analyses, September 1978.

8. K. Büttner, Physik. Bioklimat., Leipzig, 1938; H. Pfliderer and K. Büttner, Bioklimatologie, Lehrbuch für Bäder- und Klimaheilkunde, 1940.

9. *Global Atlas of Relative Cloud Cover 1967-70*, a joint production of the National Oceanic and Atmospheric Administration, National Environmental Satellite Service and U. S. Air Force Air Weather Service (MAL), USAF Environmental Technical Application Center, September 1971.

10. L. H. Allen, Jr. and H. W. Gausman, *Penetration of Solar Ultraviolet Radiation into Terrestial Plant Communities*, CIAP Monograph 5, Part 1, Chapter 2, Department of Transportation Climatic Assessment Program, September 1975.

11. A. E. S. Green and T. Mo, *Erythema Radiation Doses*, CIAP Monograph 5, Part 1, Chapter 2, Appendix I, Department of Transportation Climatic Assessment Program, September 1975.